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A CHRONOSEQUENCE OF SOILS
NEAR THE FRANZ JOSEF GLACIER

A thesis
submitted in partial fulfilment
of the requirements for the Degree
of
Doctor of Philosophy
in the
University of Canterbury

Peter R. Stevens
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I

INTRODUCTION

Professor Hans Jenny, in his book "Factors of Soil Formation", wrote (p.31)

"The estimation of relative age or degree of maturity of soils is universally based on horizon differentiation. In practice, it is generally maintained that the larger the number of horizons and the greater their thickness and intensity the more mature is the soil. However, it should be kept in mind that no one has ever witnessed the formation of a mature soil. In other words, our ideas about soil genesis as revealed by profile criteria are inferences. They are theories, not facts. This accounts for the great diversity of opinion as to the degree of maturity of specific soil profiles. It is well known that certain eminent pedologists take objection to the general belief that chernozems are mature soils; others consider brown forest soils and gray-brown-podsolic soils merely as immature podzols. The list of controversial soil types is quite long. Whatever the correct interpretation may be, it is evident that the issues center around the factor time in soil formation."

One method of studying the effects of Time as a Soil Forming Factor is the recognition and investigation of a Chronosequence, wherein four of the five Soil Forming Factors are kept constant or ineffectively varying. Thus, observed differences between soils of different ages forming a sequence are deemed to be the result of the lapse of varying intervals of Time since the initiation of soil formation.

It is helpful to assign accurate ages to the soils of such a Chronosequence, allowing the derivation of Chrono-functions - rate-equations of soil formation. In many parts of the world, intermittent alteration of the Earth's

surface by mudflows, volcanism or processes of glaciation has provided areas of terrain whose relative and absolute ages can be determined by the techniques of the botanist and geomorphologist with some degree of confidence. [Such an area occurs in the vicinity of the Franz Josef Glacier, which has at various known times deposited morainic and alluvial debris in defined places.] A succession of plants has colonised these ground-surfaces, and on them a Chronosequence of soils has developed concomitantly. Deposition of organic matter in and upon the parent material initiates depth-gradients of many soil characteristics such as reaction, bulk-density, and contents of organic carbon, nitrogen and various fractions of phosphorus. Under the influence of a warm and extremely humid climate the processes of weathering and leaching within the soil profile are responsible for striking gains, losses, transformations and redistributions of many organic and inorganic constituents.

Some of these changes have been studied during the past four years, following an earlier investigation by the present author of the most youthful soils of the Chronosequence in 1962 and 1963. This initial work traced the development of six ecosystems 0, 6, 12, 25, 45 and 55 years of age. Spectacular accretion of nitrogen, especially, showed no indications of having reached any apparent steady-state in the oldest ecosystem, despite the impending elimination from the botanical succession of Carmichaelia grandiflora, a native legume. Clearly, it was important to determine nitrogen contents and the point of steady-state of nitrogen in soils older than 55 years, which lack any plants known to be capable of nitrogen fixation. In addition, the recognition of older soils,

whose position on an orderly continuum of soil development could be assumed with some degree of confidence, would provide considerable information about rates of change of many other aspects of soil morphology, mineralogy and physical and chemical characteristics.

This thesis is organised in the conventional manner. The breadth of investigation, involving aspects of glaciology, geomorphology and ecology as well as pedology, has necessitated a lengthy Review of Literature embracing facets of Chronosequences, geochronology, podzolisation and gleying, and podocarp successions in New Zealand, as well as a brief review of the previous study. A lengthy period of field-work has been encompassed by a few brief notes in the section on Materials and Methods, followed by a presentation of Results, and ensuing Discussion. For easy reference, the Tables, Figures, Plates, Appendices and References have been bound within a separate volume.

Finally, it is relevant to comment upon the scientific and utilitarian value of such a study. Firstly, this study, conducted by what A. Rode has called the "Comparative Geography Technique", is necessarily a "static" study. Selection of soils from various points along a Time-sequence of soils presupposes that consecutive members of the sequence have at one time passed through, and been identical with, the stages of development represented by all members preceding them in the sequence. This is an assumption which a priori cannot be proved. Secondly, the study does not deal with the "dynamic" diurnal or seasonal changes within and between ecosystems. Nevertheless, the recognition of successive ecosystems, accurately dated, has enabled the establishment of a "Natural Laboratory" in which other

studies of microfauna and flora, mineralogy and weathering can be and are being conducted. Insofar as soils exhibiting varying degrees of development are often found on geomorphic surfaces of differing ages within New Zealand, the chronosequence concept could provide a useful tool in geomorphology and geochronology. The provision of information about a group of soils little understood by agronomist or forester might also be a worthwhile result of this study. It may have thrown some light on what might be termed the "Birth, Life and Senescence" of a West Coast soil.

II

REVIEW OF LITERATURE

II 1. CHRONOSEQUENCES

II 1.1 Theoretical Considerations

The Chronosequence and the soil forming factors

The Glossary of Soil Science Terms (1965) defines a Chronosequence as

"A sequence of related soils that differ, one from the other, in certain properties primarily as a result of time as a soil forming factor".

A more specific definition might be

"A sequence of soils developed on similar parent materials and relief under the influence of constant or ineffectively varying climate and biotic factor, whose differences can thus be ascribed to the lapse of differing increments of Time since the initiation of soil formation".

If the Fundamental Equation of Soil Forming Factors (Jenny, 1941, 1946, 1958, 1961; following Dokuchaev, 1951, and Shaw, 1930)

$$s = f(cl, o, r, p, t...)$$

is evaluated for Time a Chronofunction is expressed as

$$s = f(T_{cl}, o, r, p...) \quad (\text{Jenny, 1961})$$

that is; the magnitude of any soil property (s) is functionally related to Time if the subscripts Climate, Biotic Factor, Relief, Parent Material and other factors (three dots) are ineffectively varying. The inclusion of all factors within the parentheses (Jenny, 1961, compared with Jenny, 1941) is intended to emphasise that the partial derivative of the property with respect to these factors is nearly zero, not that the factors are necessarily held constant.

Jenny insisted that the soil forming factors act independently, and that the extent of soil development be measured with reference to a Time Zero. If the nature of the Time factor is to be investigated all the other soil forming factors must be kept constant or ineffectively varying. If they vary effectively the path of soil development is interrupted and a new Time Zero must be taken. According to Crocker (1952), variations must be sudden, for slow adjustments lead to "an elusively migratory Time Zero". In practice this restriction leads to a great deal of difficulty and virtually confines investigations to monogenetic ("ontogenetic", Nikiforoff, 1942) soils.

"One serious objection to the factorial method of studying soil development is an implied assumption, not so stated, that soils are monogenetic; that is, they were developed under constantly uniform conditions since their initial state. Such a condition is true only for very young soils, those not older than the last ice age" (Barshad, 1964, p.60).

This has been a serious difficulty in quantitative investigations and interpretations of soil sequences and functions, using the ideas Jenny developed in his papers published in 1946, 1958, 1960 and 1961, and in Harradine and Jenny (1958). Jenny (1958) illustrated sequences and functions of soil forming factors with large hypothetical models of ecosystems, and later (1961) considered the ecosystem per se and derived State Factor Equations based on the fluxes and potentials of matter and energy through its arbitrary boundaries. Thus, ecosystem properties are a function of the three State Factors:

1. the assemblage of properties at Time Zero (PM, Relief)
2. the external flux potentials (Climate and Biotic Factor); and
3. the age of the ecosystem.

Jenny (1960) used the relationship between precipitation and nitrogen values of some soils in northern India to illustrate the contribution of any State Factor \underline{F} to the variation of any soil property \underline{P} , given by

$$\int_c^d \frac{\sigma \underline{P}}{\sigma \underline{F}} \cdot d\underline{F}$$

There are two parts to this expression

1. the "range" (c to d) of \underline{F}
2. the "effectiveness" of \underline{F} ($\sigma \underline{P} / \sigma \underline{F}$)

Thus, the contribution of \underline{F} to variation of \underline{P} in a given area becomes negligibly small if

1. the range of \underline{F} is small (constancy of factor), and/or
2. the partial $\sigma \underline{P} / \sigma \underline{F}$ is near to zero (effectiveness is small).

In the latter case, the factor need not be kept constant, as any change will not significantly affect \underline{P} .

Jenny's theories have been discussed at length by Major (1951), Crocker (1952, 1959), and several other authors, notably Stephens (1947, 1951). Major and Crocker made their greatest contribution in clarifying the concept of the Biotic Factor, which might appear to be the least independent of all the soil forming factors. Stephens (1947) felt strongly that the factor Time is the only truly

independent factor, and objected to its inclusion in the Fundamental Equation. Time is an anomolous factor, having no influence in itself, but governing the influences of the other factors on the soil until an apparent dynamic steady-state is achieved. Enlarging upon an equation by Wilde (1946)

$$s = \int (g. e. b.) dt \text{ (where } g = \text{geological substrate} \\ e = \text{environment} \\ b = \text{biological actions})$$

Stephens integrated the soil forming factors

$$s = \int f(c, o, r, w, p) dt \text{ (where } w = \text{water table}).$$

Jenny (1941) discussed the concept of soil maturity, mentioning that not all soil components approach "maturity" at the same rate or point in time. At the point of dynamic equilibrium, or apparent steady-state, the change σs in some soil properties during a time interval σt will be represented by

$$\frac{\sigma s}{\sigma t} = 0$$

in which case Time can be neglected since it has no further effectiveness. Very slow rates of change may be mistaken on the human time-scale for apparent steady-states. Jenny also mistakenly assumed that a solum is immature so long as water continued to pass vertically through it.

The journal "Soil Science", vol. 99 (1) (1965) contains a large number of papers considering soil forming factors and processes throughout the Quaternary. Reference will be made to individual papers later in this thesis, but it is perhaps relevant to note the contribution of Bidwell and Hole (1965), establishing Man

as a factor of soil formation. Yaalon and Yaron (1966) coined the term "Metapedogenesis" to describe man-induced processes and changes in the soil profile, the consideration of which will become increasingly important in the future.

Finally, it is apposite to quote Walker's (1965) observation (p.295):

"In one of the few critical appreciations of Jenny's contributions, Crocker (1952) concludes that polygenesis of soil is the rule rather than the exception, and monosequences, where only one of the state factors varies significantly and which are of the greatest scientific value in the derivation of functions relating soil properties and the state factors, are likely to be both short and approximate. Although much may be gained from the study of polysequences, both Jenny (1958) and Crocker (1952) stress the great need to deliberately seek out those rare monosequences which, intensively studied, should indicate the most important trends and processes in pedogenesis".

Soil Development

Having now briefly discussed some of Jenny's theories and considered their impact upon studies of soil formation, it is necessary to mention some specific aspects of soil development.

Byers et al. (1938) dealt with soil formation in a general manner, but a more detailed exposition of the chemistry of soil development has been presented by Barshad (1964). In particular, he gave an exhaustive list of the analyses necessary to obtain data for elucidating profile development, which included (p.4)

- "1. Removal and determination of organic matter.
2. Removal and determination of uncombined oxides, carbonates and soluble salts.
3. Extraction of the clay fraction and its determination in soil freed from organic matter and uncombined oxides.
4. Total chemical analysis of the clay fraction freed from organic matter and uncombined oxides and saturated with a known exchangeable cation.
5. Total chemical analysis of the whole soil also freed of organic matter and uncombined oxides and saturated with the same exchangeable cation as the clay fraction.
6. Cation and anion exchange properties: exchangeable bases, exchange acidity, and total cation and anion exchange and fixation capacities for various cations and anions.
7. A mineralogical analysis of the soil, which should differentiate clearly between the clay and non-clay fractions....
8. A morphological analysis of the soil should include a macroscopic and microscopic description of the various minerals, aggregates and voids as to shape, size and arrangements with respect to each other and with respect to soil depth and lateral extension...."

Barshad's contribution is notable for the emphasis he placed upon establishing uniformity of Parent Material (PM)* prior to measuring the subsequent changes due to soil formation. Heavy reliance is placed upon mineralogical analyses, and particularly upon the particle-size distributions of and ratios between resistant "index" minerals such as zircon, tourmaline, garnet, anatase, rutile, quartz and albite. In view of the demonstrable instability of some varieties of quartz, garnet and zircon (Raeside, 1959), these analyses should perhaps be interpreted with caution. Raeside stated that non-resistant quartz, garnet and zircon should not be used as index minerals in old soils, or in soils subjected for

*In this thesis, the plural of PM is PM's.

long periods to high rainfall. Nevertheless, despite the precautions necessary, and despite the fact that his sampling methods are essentially limited to non-stony soils, Barshad's calculations represent an important technique in "quantitative pedology". For example, after applying his methods to a wide range of soils, he was able to make the following observations (inter alia) about the relationships between clay formation, clay migration and the factors of soil formation (quoted or adapted from pp.27-29):

1. Clay formation decreases down the profile, with the exception that maximum clay formation is not at the surface but in an intermediate horizon.
2. Clay migration is the most important process in the occurrence of any horizon of clay accumulation or claypan formation.
3. "In the transformation of a parent material to a soil material, clay formation is mainly responsible for the changes in mineralogical composition, but clay migrations, reflected by losses or gain of clay, are mainly responsible for the changes in chemical composition".
4. "An increase in both temperature and rainfall increases total clay formation of a given parent material...."
5. "Topographical conditions which decrease the effective drainage of a soil appear to enhance rate of clay formation".
6. "Grass-type vegetation is more effective in promoting clay formation than tree-type vegetation".
7. The effect of igneous, metamorphic or sedimentary parent materials is important only insofar as the properties of mineralogical and chemical composition, mineralogical texture, porosity, density, structure and fabric, and degree of consolidation, are affected.
8. "Even under the most intense weathering conditions, as in Latosols, the annual rate of clay formation is very small, ranging from 0.0001 to 0.002g per 100g parent material".

Discussing chemical changes in uncombined iron oxides Barshad had this to say (p.65):

"The presence of distinctly different soil types does not imply that the natures of the soil-forming reactions themselves are different in each soil, but rather that the relative importance of different soil-forming reactions is different in each soil".

This concept has been expanded in a classic paper by Simonson (1959), in which he postulated that many very different kinds of changes within soils, including additions of organic matter (OM), removals of soluble salts and carbonates, transfers of humus and sesquioxides, and transformations of primary minerals into secondary minerals, (and many others) all proceed simultaneously in all soils. The balance between these combinations of effects determines the present and ultimate nature of the soil profile.

"Thus, the processes in horizon differentiation in Podzols would be the same as those in Latosols, Chernozems or Desert Soils".

Of course, the balance between and relative importance of the many processes is not the same for each soil, and can even change with Time within a given profile. The concepts are elegant, and may be extended to the formulation of multiple working hypotheses in soil genesis, as outlined by Arnold (1965), whose pictorial models are graphic illustrations of soil formation and the action of the soil forming factors. Another approach to the differentiation of major soil groups is that of Crompton (1960), who clearly illustrated that weathering and leaching are

"distinct processes which do not vary directly with each other nor equally with each particular variation in environment".

Much Russian work, hitherto unavailable, has been presented in the monograph by Rode (1961) - an admirable attempt to clarify difficult and contradictory concepts. Only a few aspects of this work can be mentioned here. Rode has given the name "comparative geography" to the sequential method of studying soils, wherein it is postulated that consecutive members of any Time-sequence of soils have passed through, and their stages of development may be represented by, all members preceding them in the sequence. He stressed the dangers inherent in theorizing too extensively when all factors of soil formation other than Time may not have been kept constant during the development of the soil.

Rode later discussed the irreversible nature of some soil forming processes such as weathering and loss of matter from the solum, giving small increments of change, the totality of which are detectable as a series of finite alterations within the soil - its evolution. Soil evolution is the result of "a continuously advancing soil forming process" determined by the factors of soil formation. Without mentioning Jenny's contributions to this topic, Rode is inclined to add three more soil forming factors to the original five: the economic activity of Man, the earth's gravity, and the ground, soil and surface waters. Finally, he discussed the concept of an equilibrium or steady-state in the evolution of a soil, and insisted that the self-development of a biogeocenose (=ecosystem) could never reach equilibrium. Nevertheless, he conceded that rates of change during this stage of equilibrium could become so slow as to be undetectable.

It might be said that Pedology as a science has finally come of age, having passed from the purely descriptive and qualitative to the point where analytical, mechanistic and quantitative experiments may be attempted. The volume "Experimental Pedology" ** is a welcome indication of this progress, and reference will later be made to a number of papers it contains. The paper by Walker (1965) demonstrated the inherent possibilities of quantitative pedology. Not only did it detail studies of the Time and Climate factors (Chrono- and pluvo-sequences of basalt-, greywacke- and schist-derived soils), the Parent Material factor, and the factor Man, but it related these to the significance of phosphorus in pedogenesis, and to the gains, losses and redistributions of matter due to various soil forming processes.

** "Experimental Pedology". Proceedings of the Eleventh Easter School in Agricultural Science, University of Nottingham, 1964; ed. E.G. Hallsworth and D.V. Crawford; pp. 414. Butterworths.

II 1.2

Non-Strict Chronosequences

It is intended to outline briefly in this section some of the many studies of soil formation in which constancy of the soil forming factors other than Time has been insufficiently established, or in which it was not possible to date ground surfaces accurately. Lack of space will unfortunately preclude discussion of other types of sequences such as Climosequences (Lee et al., 1964; Macvicar, 1965; Tidball, 1966) and Toposequences (Watson, 1964/65; Floate, 1965; Lee and Ryan, 1965; McKeague, 1965a; Wilding and Rutledge, 1966), interesting as they may be. Nor will it be possible to discuss aspects of botanical succession on glacial moraines and other fresh deposits of PM (Zach, 1950; Lawrence, 1951; Cooper and Rudolph, 1953; Stork, 1963; Jacks, 1965) although these and similar studies often mention some concomitant changes in the soils under the various seral associations. The following section (II 1.3) will discuss a number of Chronosequences in which constancy of the soil forming factors and ground surface dating have probably been satisfactorily achieved.

Mineralogical changes may often be related to Time, and may even become a useful tool in geomorphology. An example is the use of CaO-ZrO_2 molar ratios as an index of weathering by Beavers et al. (1963), who demonstrated that major loess deposition ended in southern Illinois about 11,000-11,800 years ago, and that the first two-thirds of the loess was deposited faster than the most recent portion. Although the six soils investigated were termed a Chronosequence, the study bears a closer resemblance to C.E. Hutton's (1950) "Chrono-Lithosequence" in Iowa, in which he showed that the effect of PM is most important in

soils occurring on the first 60 miles of a 170 mile transect distally from the loess source, whereas Time determined degree of development for the section from 60 to 170 miles - a Chronosequence. Another soil property which has been shown to change in an orderly manner with Time is authigenic carbonate accumulation in some desert soils on Mid- and Late-Pleistocene surfaces in New Mexico (Gile et al., 1966; Gile, 1967). They traced the development of thin and then thick carbonate coatings, followed by interstitial carbonate plugging and the formation of laminar layers on top of the K (German:Kalk) horizon, and were able to confirm this sequential development with radiocarbon dates. Similarly, White (1967) related development of parallelepiped subsoil structure to age of four soils in North Dakota.

The relative proportions and distributions within and between horizons of the inorganic phosphorus fractions may also change with Time (Allaway and Rhoades, 1951; Godfrey and Reicken, 1957; Gotoh and Matsuo, 1963; Williams, 1965). Gotoh and Matsuo, working with poldered soils 0, 3, 5, 50-70, 300-500 and 500-700 years of age, presented rather generalised conclusions and did not fully utilize a promising situation. Williams, as well as developing the phosphorus fractionation scheme used by the present author, was able to detail many trends in phosphorus fractions within and between the profiles of a weathering sequence of basalt-derived soils. His conclusions will be referred to later in this thesis.

Since they contain man-made soils of precisely-known age, polders might present good opportunities for Chronosequence studies. Jenny (1941) mentioned Hissink's (1938) study of decalcification during some 300 years of

soil formation. In contrast to studies of decalcification of sand-dunes (Salisbury, 1925), it is interesting to note that empoldered soils require a lengthy period of "ripening" (Dutch:rijping), to reduce salinity and create favourable conditions for free drainage, before carbonate contents decline appreciably. Pons and Zonneveld (1965), Ente (1967) and others have detailed the processes of initial soil formation in Dutch polders and marine muds elsewhere in the world. The major chemical processes are concerned with oxidation of reduced compounds such as sulphides.

Just two of several investigations of the development of a soil microflora in early stages of succession on sand-dunes may be mentioned. Webley et al. (1952) showed progressive increases in bacterial and fungal populations with the introduction of colonizing plants and the development and increasing complexity of the communities. They also demonstrated a considerable dependence (rhizosphere effect) of microflora on the root systems of colonizing grasses in the early successional stages. This was confirmed by Wohlrab and Tuveson (1965) in Indiana dune sands; the change from the harsh environments associated with Ammophila sp. on bare sand to relatively favourable conditions under Andropogon sp. produced a very considerable increase in numbers of fungal species and individuals. Barratt (1962) studied microfaunal changes under successional associations at Seaton Sluice, and related these to morphological changes, which have also been studied by De Coninck and Laruelle (1964). These workers showed progressive micromorphological change towards podzolisation in sandy soils of the Belgian Campine, and were able to use these studies as an aid in

soil survey. An organic or mineral cutan is first formed around the skeleton particles, which later leads to translocation of clay and other plasma elements, giving humic podzols with iron pans on most PM's, and mottles and iron concretions on glauconitic PM's.

Invasions of cleared areas by trees, or changes in the nature of plant associations, have always provided fruitful opportunities for the investigation of quantitative correlations between vegetational changes and soil development. Billings (1941) has reviewed some previous studies. Six representative papers may be selected from the voluminous literature on this topic: Coile (1940), Gorham (1953), Ike and Stone (1958), Olson (1958), Atkinson (1959) and Mackney (1961). Coile reported increased A_0 horizon depth, %organic C and C/N ratios, with decreased infiltration rates despite virtually unchanged volume-weight, water-holding capacity and pore-space after invasion of abandoned agricultural land by loblolly pine. Gorham's study, a "chronological sequence" from an inorganic lake bed to a raised bog, showed increased acidity and decreased %BS and %N through the sequence. Ike and Stone reported significant accumulation of nitrogen (approximately 600 lb/ac./20" depth) under Robinia pseudoacacia, a leguminous tree, compared with adjacent forested areas. There were no differences in pH, OM, bulk density and "easily-extracted" phosphorus and potassium between these areas. Olson dated (by radiocarbon) some sand-dunes to the south of Lake Michigan, and established interesting connections between the composition of the PM and dominant climax species. Total N attained a steady-state within the first 1500 years of soil development in the upper 10cm horizon. Atkinson was

able to correlate poor growth of Pinus radiata with low soil phosphorus content rather than any other parameter. Mackney traced the development of podzol intergrades, iron podzols and eventually humus-iron podzols, under a vegetation sequence of oakwood to heath.

The Time factor in litter production has been briefly discussed by Bray and Gorham (1964), under the headings Seasonal Variation, Annual Variation, and Age of Stand. They pointed out

"In no case has litter-fall been followed through a generation in an individual stand, so that all studies of age effects have been based on diverse stands of different ages. The results of such studies are also rather diverse."

They reviewed several studies, the general conclusion being that little variation in litter-fall within a wide range of European forests is evident from 30 to more than 100 years of age.

Finally, a number of miscellaneous studies must be mentioned to illustrate other possible approaches to the investigation of soil sequences. Ostendorff (1964) showed how the permeability of the PM can greatly influence the ultimate soil developed on postglacial surfaces. Peats and gleysols are found on impermeable deglaciated rock or compact tills, whereas on properly-drained sites a number of AC-profiles (lithosols, rankers, rendzinas, chernozem-like soils) may develop at first, changing to mull Braunerdes with time. On the other hand, podzols may develop in coarse and extremely well-drained sediments. Retzer (1954) studied soil development on surfaces left by glacial retreat in Colorado, but his treatment is rather qualitative and little care was taken to ensure constancy of the soil forming factors other than Time.

Parsons et al. (1962) compared the profiles of seven prehistoric mounds of known age with adjacent, virgin, loess-derived soils. The mounds exhibited progressive development according to age; the highest rates of development occurred during the first 1000 years. The oldest profiles (less than 2,500 years) resembled in many respects the 14,000 year-old virgin soils.

In New Zealand, McCraw (1962) discussed pluvo- and alto-sequences in mountain soil patterns of an area partly glaciated within the past two millenia. His main contribution lies in the recognition of the differing effects of various PM's developed from the same parent rock - few soils are directly underlain by rock but most are developed on weathered rock, solifluxion debris, scree, colluvium, fans, loess and alluvium. Despite similar chemical constitution, the range of physical properties displayed by such PM's may lead to widely-differing soils. Degrees of development in soil sequences from basalt and greywacke have been investigated by Wells (1959), using the growth of sweet vernal (Anthoxanthum odoratum) to assess element availability. For instance, a Time-sequence (related to time since eruption) of basalt-derived soils in North Auckland covered all stages of soil development from lithosol to mature brown loams with ironstone, and showed increases of secondary clay minerals such as metahalloysite, and goethite and gibbsite, with progressive losses of Na, K, Mg, Ca, Sr and Ba, slight losses of Cu, Zn, Si and P, little change in Zr, Mo, Mn, Co and Ni, and slight accumulation of Al, Ga, Ti, V, Cr and Fe. These analyses could be compared with those from a sequence of greywacke-derived soils, before and after podzolisation.

The K-cycle system developed by B.E. Butler has been used by a number of workers in Australia, such as P.H. Walker and D.C. van Dijk, to study soil formation on cyclic terraces and hillslopes. For example, Walker (1962) was able to assign radiocarbon dates to four cycles of erosion and deposition evident in the soils near Nowra, New South Wales. He showed that the K_3 cycle commenced 29,000 years ago (Würm I-II interstadial), the K_2 cycle 3740 years ago, the K_1 cycle 390 years ago, and the present epicycle (K_0) 0-120 years ago. These dates do not correlate with other proposed dates for past climatic events. The soils on the terraces changed from lithosol-like deposits (K_0) to minimal prairie soils (K_1), grey-brown soils (K_2) and red podzolics on K_3 terraces. Unlike McArthur and Bettenay (1960), who described ancient podzolic soils and laterites on old landsurfaces in Western Australia produced by early Pleistocene events, Walker and others (such as Blackburn et al., 1965) have found only relatively young soils near the south-eastern coast of Australia. A novel approach to the arrangement of a "Topo-Chronosequence" by the use of an erosion-potential parameter (White, 1964) showed that lithosols, non-gilgaied Chestnut soils and wavy-gilgaied soils, all formed from shale, occurred where erosion decreased progressively and thus soil age increased. Despite the author's assertion, the three soils do not form a Chronosequence since Relief and PM were not held constant, and since the oldest soils, at an earlier stage of development, were not necessarily identical to the youngest soils. Similarly, Wright et al. (1959) purported to study a Chronosequence of Alluvial, Brown Wooded and Grey Wooded soils on alluvial deposits in the Northwest Territories, but did not attempt to date the surfaces or

to hold PM and Relief constant. However, their data traced the accumulation of OM in the upper part of the calcareous PM's, removal of calcium and magnesium carbonates, and eventual eluviation of clay and leaching of iron and aluminium relative to silica, resulting in a siliceous eluviated A₂ horizon overlying a clay- and sesquioxide-enriched B horizon.

II 1.3

Chronosequences

In a letter to this author on June 14, 1966, Professor Hans Jenny stated:

"We speak of chronofunctions when soil properties and ages are known quantitatively. If the ages are relative, we speak of chronosequences. There are various degrees of reliabilities of chronosequences."

It is the purpose of this section to examine a number of the more reliable Chronosequences, and to attempt to draw some conclusions from them.

So far as this author is aware, there have been no comprehensive reviews of the topic since the relevant section in Jenny's book (1941) was written. Jenny described some studies on experimental weathering by Hilger, Geikie, Goodchild and Hirshwald, Hardy and van Baren's work on volcanic deposits, and Schreckenthal and Hoffman's work near the Mittelberg Glacier. Tamm, Mattson and Lönnemark, and Aaltonen studied rates of podzolisation in various soil sequences in Scandinavia. Two major conclusions emerged from these three studies:

1. Perceptible podzolisation had occurred within 100 years of the drainage of Lake Ragunda in Sweden, but Tamm estimated that a normal podzol with 4" of raw humus overlying 4" of A_2 and 10-20" of B horizons required up to 1,500 years to develop. Since older soils (up to 7,000 years of age) did not exhibit horizons of greater magnitudes, horizon differentiation had evidently reached an apparent steady-state.

2. The zone of maximum accumulation of sesquioxides had moved upwards within the profile in an asymptotic fashion.

Two other studies reviewed by Jenny were those of Salisbury (1925) on sand-dune sequences in England, and Hissink's (1938) study of soil processes after the reclamation of Dutch polders.

Burges (1960) reviewed a few of the above investigations together with his own work in Australia (Burges and Drover, 1953) and some examples of studies on tropical forest successions. A slightly different approach was taken by Dimbleby (1965), who discussed some of the Post-Glacial changes in soil profiles evident from archaeological and palynological investigations on some British soils cultivated in Neolithic times. Another review, by Stevens (1963), covered many of the important Chronosequences, and some aspects of these papers will be recapitulated in this section, together with accounts of others. It is possible to group the investigations broadly according to the types of landsurfaces: man-made situations, aeolian and drift deposits such as sand-dunes, and surfaces deposited by glacial or alluvial action.

An interesting "quasi-archaeological" experiment, designed to continue for 128 years, has been described by Proudfoot (1965). This may represent the first attempt to study a Chronosequence by a method other than the "comparative geography" technique, provided full advantage is taken of a promising situation. At least two other investigations utilizing man-made deposits (Leisman, 1957; Bridges, 1961) traced some aspects of progressive soil development on iron-ore spoil banks of known age. Leisman showed increases in %N with decreasing C/N ratios under Trifolium repens and Melilotus alba on six surfaces, the oldest being 51 years of age. There was minimal development of an A₀ horizon after this time, no B horizon

could be distinguished, and no trends in weathering of the soil mechanical separates could be discerned, as the PM was physically rather variable. Bridges discussed progressive increases in structural development and intensity of gleying, and also demonstrated the importance of aspect in retarding or advancing soil forming processes relative to the time elapsed since their initiation.

Some effects on soil formation of Man's agronomic and forestry practices are illustrated by two studies. Walker, Thapa and Adams (1959) found that addition of 500lb of fertilizer phosphorus to a Yellow Brown Pumice soil during 25 years of farming had stimulated legume growth and increased the N content of the 0-8" layer by 2640 lb/acre, the organic C content from 53,000 lb/acre to only 56,000 lb/acre, and thus decreased the C/N ratio from 30 to 12. The OM changed from a mor-type to a mull, and 460lb of the added P was recovered in the 0-8" layer, about half in the organic form. This was a graphic example of the speed with which some soil characteristics may readjust themselves to new apparent steady-states. Similarly, Ziemer (1964) found that the conservation of water during summer within forest clearings produced by logging 1, 5, 10 and 12 years prior to sampling decreased as the clearings regenerated. After winter equilibration to field capacity in both clearing and surrounding forest, the summer moisture differential between clearing and forest was at a maximum where the clearing was youthful, but became progressively smaller as the clearing regenerated - the moisture savings in the clearing being 6.9", 2.9", 1.2" and 0.7" of water per 4' soil depth for the various times since logging.

Aeolian deposits, such as sand-dunes and loess, may often be dated accurately, and have been profitable sites for Chronosequence studies. Mention has already been made of Salisbury's (1922, 1925) dune-sequences at Blakeney Point and Southport, which showed a decrease of $\%CaCO_3$ from 6.3 to 0.09 in 280 years, while pH dropped from 8.2 to 5.5, OM increased from 0.5% to 15%, and the vegetation changed from calcicole to calcifuge species. Gorham (1958) traced the loss of soluble salts in a similar dune-sequence at Blakeney Point. Salisbury's data was earlier (II 1.2) contrasted with the rate of decalcification in Dutch polder soils (Hissink, 1938). Likewise, Wilson (1960) showed that soils of a dune-sequence at South Haven Peninsula, Dorset, gained OM progressively (0.2% to 13% in 240 years) while pH dropped (7.0 to 3.8-4.4), but only rather inadequate data were presented. As at Blakeney Point, the vegetation changed from Ammophila arenaria to a Callunetum, but the PM at South Haven Peninsula was very low (0.02%) in $CaCO_3$.

Other Chronosequences on dune-sands have been more comprehensive in treatment. Burges and Drover (1953) studied the rate of podzolisation in a sequence of dune-sands near Woy Woy, New South Wales, and largely confirmed Salisbury's results. Within 200 years $CaCO_3$ content of the 0-4" layer decreased from 3.0% to zero, and pH dropped from 8.8 to 6.1; organic C rose to nearly 0.6% from practically zero within the first 100 years, and thereafter remained steady. Despite some doubt about the uniformity of iron content in the various dunes, it was clear that appreciable accumulation of iron at 24-32" depth had occurred by 2000 years, a B horizon was prominent, and the soil was an iron podzol. After about 3000 years Angophora lanceolata replaced Angophora

intermedia, surface pH dropped sharply from 5.5 to 4.5, and typical humus podzols were present. Based on profile morphology and iron analyses, it was clear the B horizon had moved downwards rather than upwards, as predicted by Aaltonen and Mattson (in Jenny, 1941).

Three soil sequences on sand-dunes near the Manawatu River mouth in New Zealand have now been extensively studied by Syers (1967, and pers. comm.; see also Stevens, 1967) and Ritchie (pers. comm.), drawing on preliminary geomorphological work by Cowie (1963). These investigations are at present being consolidated into publications, so it is not possible to do more than briefly indicate the importance of some of the results. Syers sampled four dune-building phases (Waitarere, 50 years; Motuiti, 500 years; Foxton, 3000 years; Koputaroa, 10,000 years) and the beach sand at Time Zero, and showed rapid initial increases of oxidisable C, N and organic P, with decreasing rates of accumulation after 3000 years. An apparent steady-state of these constituents was almost achieved, the mean weight of total P dropped approximately linearly from about 5000 to about 3000 kg/ha/m. profile while the %P_o increased from 3.3 in beach sand to 4.8, 14.0, 25.6 and 44.6 through the sequence. Fractionation of inorganic P showed a rapid linear decrease in the percentage of total P that was calcium-bound from some 60% to virtually zero in Koputaroa soils, while the percentages of "occluded-P" and "surface inorg. P" rose steadily. An important discovery was the presence of apatite inclusions within the primary ferromagnesian minerals hypersthene and augite, and within plagioclase feldspars. This primary Ca-bound P is pedogenetically unavailable. Ritchie, working on a man-made sequence of

Pinus radiata plantations on Waitarere dunes, has traced the biomass increases in various components of the ecosystem, and accretion of N to the soil.

This brings us to a consideration of five other papers which followed ecosystem changes under afforestation by Pinus species: Ovington (1950), Wright (1955/56) and Wright and Will (1958) on the Culbin sands, and Ovington (1951) on the Tentsmuir sands. Although there were many minor variations among these studies, they all tended to show similar broad trends in soil development, some of which are summarised below:

1. Afforestation tended to reduce the amplitude of moisture and temperature fluctuations, but had little or no effect on the proportions of mechanical separates. Tree roots removed large amounts of water and lowered the water table.

2. Large progressive additions of OM decreased bulk densities of surface horizons, conserved water, and contained considerable amounts of C and N.

3. Stabilization of sand had a marked effect on the amounts and distributions of nutrient elements. Under young trees removal of nutrients (especially Ca, K) exceeded return, but after 20-25 years the canopy closed and the organic cycle helped to replenish the meagre nutrient stock by drawing nutrients from lower horizons in the profiles.

4. Numerous depth-functions for various elements illustrated the general effect of the organic cycle in concentrating most elements in surface organic layers or upper horizons, with the exception of Na.

5. The N content of Corsican Pine, to take only one example, increased from 72 to 91 and 165 lb/ac. in stands 18, 28 and 48 years of age. The percentage of N held in bark and wood, compared with that held in needles and branches, rose from 34 to 45 and 53%, an indication of possible nutrient loss after logging.

Land forms produced by catastrophic phenomena such as volcanic action, floods and glaciation have often provided superb opportunities for the recognition of soil sequences. The next part of this section will detail a number of such studies, as many are relevant to the present investigation.

Tezuka (1961) recognised a Chronosequence of basalt-derived soils on the island of Oshima in Japan. The vegetation succession passed from Carex spp. on the bare lava ('petridesert') to an Alnus sieboldiana scrub association, and thence to a mixed deciduous-evergreen forest with an evergreen climax association of Shiia sieboldiana and Machilis thunbergii. Soil development was greatly retarded at first by the inhospitable environment for plants on the petridesert, but eventually maximum total soil N (990 g/m^2) was reached in less than 1000 years, while OM increased slowly at about $2.5 \text{ g/m}^2/\text{annum}$. Aspects of theoretical plant ecology were discussed at length but the pedological value of an excellent situation was not fully exploited.

The first of three classical Chronosequences by Crocker, Dickson and Major dealt with a sequence of mudflows on the southeast slopes of Mt. Shasta, California (Dickson and Crocker, 1953/54). On various lines of evidence five surfaces of ages 27, 60, 205, 566 and 1200+ years of age were recognised, but these dates have

recently been questioned (Jenny, 1965; and pers. comm.). However, the sequence and the trends in soil formation remain the same. Several species of N-fixing higher plants (Alnus viridis, Purshia tridentata, Ceanothus spp.) were prominent on younger surfaces, leading to climax vegetation of Pinus ponderosa and Pseudotsuga taxifolia. Total soil C and N showed steady-states after about 400 years, while C/N ratios rose from about 6 to 18, with higher ratios in upper horizons and litters than lower horizons. About 3360 lb/acre (380 g/m^2) of N accumulated within 60 years. Depth functions of both C and N showed progressive accumulation in upper horizons for the first 200 years, and later translocation to lower in the profile. Changes in several soil characteristics, such as pH, bulk density and cation exchange capacity, were closely related to the addition of OM. Dickson and Crocker made two major conclusions:

1. There are two 'phases' of soil development - (a) the germination and survival of the effective disseminules, giving profiles with upper layers dominated by OM and lower layers carrying the impress of the inorganic PM; and (b) the later evolution of the profile due to weathering and eluviation of sesquioxides.

2. Mineralogical and particle-size analyses failed to show any appreciable weathering and clay formation.

A type of Chronosequence exemplified by inverted alluvial time-laminated mineral profiles near the Nile (Jenny, 1962) showed N depth-functions essentially similar to Brunizems in California, although the genesis of the two soils must be entirely different. The calculations of surface gains versus sub-surface losses of N within the layers, buried annually by 1mm of N-rich mud, represent a

novel approach to the problem of palaeosols, and a further extension of Jenny's theories of quantitative pedology.

The Chronosequence concept has found its greatest applicability in recently deglaciated areas, for it is here that accurate dating (see II 2.1) and reasonable control over Climate, Biotic Factor, Relief and PM may become possible. Among the first to understand the significance of glacial retreat for studies of soil development were Schreckenthal and Hoffman (in Jenny, 1941), but Ludi (1945) soon followed with his lengthy exposition of soil development and vegetation succession near the Aletsch, Rhone and Grindelwald glaciers. Alnus viridis was a pioneer, together with several other N-fixing Angiosperms (Dryas octopetala, Trifolium pallescens), and the oldest association (85 years) near the Aletschgletscher contained Larix decidua and Betula pubescens. Very few soil analytical data were given, but mechanical analyses showed coarse sand decreased from 62% to 34% (and fine sand increased from 29% to 51%) within the soils 5, 25, 45, 70 and 85 years of age. Silt increased from 6% to 11%, but there was no change in clay content.

Glacial recession in Alaska attracted early attention. Chandler (1942) showed decreasing pH and %BS, increasing OM contents and some formation of silt and clay in deposits near the Mendenhall Glacier. However, he mistakenly assumed constant soil volume-weights throughout the sequence. His major conclusion was that podzol development had not proceeded very far in 1000 years. M.E. Stevens (1963) described two podzols in the vicinity of Chandler's sampling sites, thus appearing to contradict Chandler, but did not indicate the probable ages of the

profiles. The most comprehensive and thorough investigations in this region were those of Crocker and Major (1955) and Crocker and Dickson (1957) - some of their conclusions may usefully be discussed together. The pioneer associations contained Rhacomitrium spp. mosses, Epilobium latifolium, Equisetum variegatum, Dryas drummondii and (at Herbert/Mendenhall) Lupinus nootkatensis, succeeded by Salix spp., Populus trichocarpa and Alnus spp. at 30-40 years of age. Later (70-120 years) Picea sitchensis followed the N-fixing Alder thickets, and ultimately Tsuga heterophylla and T. mertensiana dominated the forests on old (200+ years) surfaces until muskeg development occurred. The succession is clear:

1. Herb and grass pioneers, generally non-N-fixing, with their areal and floristic distribution being dependent upon the number, proximity and mobility of their disseminules, and the rate of exposure and physical characteristics of bare moraine.

2. Sub-pioneers of N-fixing higher plants, whose presence has a profound effect upon the accretion of OM and N.

3. A transition stage wherein the N-fixers are eliminated by other plants, usually conifers.

4. These dominants occupy the site for a variable but lengthy period of time, utilising the N accumulated by the sub-pioneers.

5. The inevitable processes of soil degradation may eventually allow species of lower nutrient requirement to dominate if disseminules are available, and inhospitable soil physical conditions (swamping, iron pan development)

may favour the formation of bogs with a characteristic flora.

General similarities to the Mt Shasta Chronosequence are apparent in the Glacier Bay and Herbert/Mendenhall sequences. Bulk densities, especially of surface horizons, decreased rapidly as OM accumulated. Soil reaction also decreased with time; Crocker and Major found a close correlation between plant species and rate of pH decline. There was a rapid increase of organic C content to about 9, 7 and 5 kg/m²/profile in approximately 200 years at Mendenhall, Herbert and Glacier Bay respectively, after which the rate of accumulation declined and apparent steady-states may have been achieved. The pattern of N accretion generally followed org.C closely, but C/N ratios, especially of L and FH layers, widened considerably after the 'transition' stage. At Glacier Bay there appeared to be a decline in total N after this transition, possibly related to the simultaneous demand for N by the rapidly-growing spruce forest. The apparent steady-state for N may however have been relatively transitory; within 200 years less than 0.4 kg/m²/24" profile had accumulated at Herbert/Mendenhall, whereas two "late-Glacial" moraines contained nearly 0.9 kg/m²/24" profile of N. Various depth-functions for pH, BD, org.C and N showed close similarities to those at Mt Shasta, and admirably illustrated the effects of the organic cycle in first altering the upper horizons of the PM. Unfortunately, no phosphorus analyses were made. Once again, there was a negligible degree of weathering and clay formation within the limited time-span of the Alaskan Chronosequences. Finally, the fungal successions within the deglaciated terrain near these glaciers were discussed

in considerable detail by Sprague and Lawrence (1959/60) and Cooke and Lawrence (1959).

Three further Chronosequences must be mentioned before concluding this section with a consideration of some work in Michigan. Firstly, Tisdale et al. (1966) used the preliminary botanical work of W.S. Cooper near Mt Robson, British Columbia, to arrange a Chronosequence of soils up to 160 years of age. Their reported soil data are unfortunately very scanty. Surface soil pH showed no significant trend in relation to soil age, a slight degree of podzolisation was observed, and there was very little increase in N content. A considerably more comprehensive investigation was carried out by R.P. Goldthwait and many colleagues (Goldthwait et al. 1966), again in Glacier Bay, near Muir Inlet. The study is notable for its unified and concerted consideration of very many aspects of ecological succession, and represents one of the most impressive contributions to Chronosequence studies yet made. Reports of glacial history, climate, soils (by F.C. Ugolini), plants, insects, birds, mammals and freshwater fish are all considered in relation to time since deglaciation. The Chapter on soils emphasised features previously revealed by Crocker and Major, but added to these mechanical analyses and determinations of free iron oxides, cation exchange capacity and exchangeable bases. C.E.C. increased from 2.4 m.eq./100g at Time Zero to a maximum of 16.6 m.eq./100g in an organic-rich horizon of the oldest soil (250 years). The PM contained 0.21% free Fe_2O_3 , increasing to 0.63% in the B_{ir} (5-10cm) of the oldest soil. Ugolini considered "the ontogeny of the Podzols" in this area and proposed a genetic sequence of Regosols (0-15 years) to Podzolic soils (80-100 years) to Brown

Podzolic soils (150 years) to Podzols after 250 years. Such a reconstruction is perhaps a little unwarranted, in view of the juvenile nature of the soils on such young surfaces. Another Chronosequence, in Central Alaska near the Muldrow Glacier, was studied by Veireck (1966). Five surfaces (25-30, 100, 150-200, 200-300 and 5,000-9,000 years of age) were recognised, and a limited amount of soil data presented. Some weathering of sand was apparent at the 10cm level (87% to 70% in 300 years) with a concomitant increase in silt, but little clay was formed. Alder was absent but increases of %N under Dryas drummondii, Shepherdia canadensis and the legumes Astragalus nutzotinensis and Hedysarum mackenzii were recorded. The main difference between this sequence and others described above is the development of permafrost related to the insulating effects of vegetation.

A particularly thorough study of a Chronosequence of podzols 2,500, 3,000, 8,000 and 10,000 years old (Franzmeier et al., 1963) in Northern Michigan confirmed many of the trends noted above, such as declining pH, additions of OM, loss of carbonates and removal of basic cations, but the work was notable for its elucidation of mineral weathering, clay formation, and micromorphological changes. Extractable P, Fe and Al were also determined. The absence of a soil at Time Zero necessitated several assumptions about the state of the PM, but nevertheless a coherent picture of progressive podzolisation emerged. Rather than describe the changes of each individual soil characteristic it is perhaps more satisfactory to summarize their interpretation of the genesis of the oldest soil of the Chronosequence:

1. OM is added to the original calcareous PM, reactive organic chemical groups are added to the percolating rainwater, and carbonates are dissolved and leached from the profile. A pH gradient is thus established, resulting in dissolution of primary phosphates in the A horizon and their precipitation in the B, probably as aluminium phosphates.

2. Weathering of primary ferromagnesian and feldspathic minerals, and illite and chlorite, in the A₂ mobilises cations such as Fe, Al, K and Mg, and slightly crystalline layers on sand grains in the B horizon are formed.

3. Eventually humus begins to accumulate as amorphous coatings on the previous crystalline layers, forming a B_h horizon. Aluminium phosphates may be converted to iron phosphates. The amorphous coatings increase in thickness, flake off, and form intergranular deposits, leading to increased capillary pore-space, readily available water capacity, exchange capacity and exchangeable bases.

4. During the entire course of soil formation, sands in the upper horizons weather to finer sizes. Chemical weathering converts illite and chlorite to vermiculite and montmorillonite. Clay is ultimately segregated into another eluvial-illuvial sequum below the podzol sequum.

Finally, recent microbiological work on some soils of the Franz Josef Chronosequence must be briefly mentioned, before this section is concluded. Hollings (1967a+b) conducted extensive isolation and perfusion

experiments on samples from Stages I, II and IV (see II 5.2). His main conclusions were:

1. Numbers of bacteria increased greatly with the development of a complex soil-plant relationship.

2. Azotobacter sp. were present in the youngest soil, but in the almost complete absence of energy substrate could not be considered active N-fixers.

3. All soils had very low nitrifying capacities, because of lack of energy substrates or low pH.

Stout and Dutch (1967) tested some older Franz Josef soils and noted:

1. Total bacterial populations are variable but decline with age.

2. There is a rich protozoan fauna, especially in the younger soils.

3. Respiratory rates are highest in Stage IV and VI soils (25 and 55 years of age), and lowest in Okarito soils (22,000 years old).

It seems fitting to conclude this discussion of Chronosequences by paraphrasing some observations made by Stevens (1963):

1. It is difficult, if not impossible, to ensure that the soil forming factors other than Time are held constant or ineffectively varying.

2. It is desirable to sample the whole ecosystem, rather than only mineral soil and forest floor.

3. The bouldery nature of most glacial tills makes meaningful sampling arduous, but volume-weight methods must be employed. Properly randomised sampling and a

satisfactory statistical basis for experimentation seems impossible.

4. Permanent apparent steady-states of nutrient accumulation are generally not attained in short-term studies. There are different rates of attainment of dynamic equilibrium by each soil component.

5. The initial course of soil development is directly and completely correlated with the advent, growth and areal distribution of various vegetation associations, which in their turn are affected by external factors such as location and state of neighbouring ecosystems, pre-adaption of disseminules and accidents of dispersal, and ecologic factors such as competition for light, nutrients and water.

II 2 GEOCHRONOLOGY AND PALAEOCLIMATOLOGY

II 2.1 Some Geochronological Methods

This brief section is intended to serve merely as an introduction to some aspects of dating the past. The topic has been well reviewed by Flint (1965), Zeuner (1958), Leopold et al. (1964) and others, so this will be only a cursory glance at the methodology of geochronology.

Perhaps the earliest, and the most painstaking, work in this field was Baron Gerhard De Geer's Swedish varve chronology, which covered a north-south distance of 1,000 km embracing the last 17,000 years. Despite controversy, it is at least partly corroborated by a radiocarbon date near the middle of the sequence, and has been correlated with North American chronologies by E. Antevs. Another technique demanding painstaking field measurement is lichenometry, developed by Beschel (1961, among others). A powerful and sophisticated tool for determining ancient temperatures is radionuclide ($^{16}\text{O}/^{18}\text{O}$) examination of deep-sea cores (Emiliani, 1958), and absolute dating of the same cores can often be achieved by the $\text{Pa}^{231}/\text{Th}^{230}$ method (Rosholt et al., 1961). Some results of these investigations will be embodied in later parts of this section. Still another "laboratory" method was used to estimate the ages of morainic systems of the Tazewell stadial in Indiana (Hensel and White, 1960). They found the rate of weathering of K_2O from the 2-0.2 μ fraction of surface soils was about 0.1% per 1000 years, and satisfactorily interpolated their derived dates between radiocarbon dates on the youngest and oldest moraines. Similarly, Beavers et al. (1963) dated loess deposition stages by CaO-ZrO_2 ratios in soils and PM's. It is

possible that a further method for comparative, if not absolute, dating of soils may be provided by inorganic P fractionation, particularly by measurements of the irreversible loss or conversion of primary Ca-bound forms of P.

Methods utilizing a less precise, more intuitive, approach may perhaps be discussed together. Leopold et al. (loc. cit.) have discussed at length the pitfalls inherent in the use of historical records. Spectacular geographical events may receive excessive emphasis while slow secular change is overlooked, there are problems of non-comparability of data due to lack of criteria and observer bias, and, of course, there are many gaps in the historical records. On the other hand, archaeologists have long used artefacts to date, in a comparative fashion, anthropological changes. Many excellent geomorphological investigations have aided the establishment of chronologies; just two examples being a study of ages and development of soil landscapes in relation to climatic and vegetational change in Iowa (Ruhe and Scholtes, 1956), and Fairbridge's (1960, among others) papers detailing sea-level fluctuations. The response of enclosed lakes to past and present climates has been discussed by Lawrence and Lawrence (1961). An important paper by Gage (1965) discussed the problems of age classification of glacial evidence, especially with regard to preservation of surface form and to degree of weathering of deposits. The application of such criteria as stoniness of glacial tills and distinctness of stream dissection may lead to the establishment of correlatives within and between regions - the recognition of supposedly synchronous correlatives is the least objective but most useful method employed in glacial geology.

Finally, three well-known chronological methods must be mentioned. Dendrochronology - the study of tree-rings - was developed by A.E. Douglass in the south-west of the United States, and has since been refined by W.S. Glock and many others. Lawrence (1950) described the techniques, and has successfully employed them in Alaska, South America, New Zealand and elsewhere. Using data from dendrochronology, Bray (1965) showed that the great majority of recent ice advances in NW North America occurred near the close of periods of low sunspot activity, with retreat or stagnation during the subsequent high-activity cycle. In New Zealand, Bell (1958) reported favourably upon the possibilities of tree-ring dating, but was contradicted by Cameron (1960b). However, Wardle (1963a), Lawrence and Lawrence (1965), and Druce (1966) have used these methods in various regions of New Zealand. In particular, Wardle (loc. cit.) demonstrated that most of the existing rimu (Dacrydium cupressinum) in six selected stands on Secretary Island, Fiordland, established between 1400 and 1700 AD, failed to regenerate during the 18th Century, and exhibited reduced growth increment since that time. Except in special circumstances, dendrochronology is limited to the life-span of existing trees, usually less than 500 years. Next, pollen analysis (palynology) can be but briefly mentioned; it is a field with many very talented exponents. Much detailed palaeoclimatological data, especially of the European stratigraphy, has been inferred from countless pollen profiles. Lastly, dating by radiocarbon (C^{14} , half-life = 5730 ± 20 years) and other radionuclides such as potassium-argon and protactinium-thorium have become widely respected methods. Despite many possible reasons for fluctuations of C^{14} proportions in the atmosphere

(de Vries effect, prior to 0 AD; Suess effect, since the Industrial Revolution; and the Bomb effect, post-1954 AD), and the dangers of old C^{14} from ancient carbonates being incorporated into the tests of pelagic fauna and into flooded peats, many thousands of radiocarbon dates (for example; Grant-Taylor and Rafter, 1962) have been determined. They frequently accord very well with dates derived by other methods, although the event must be carefully scrutinised to understand exactly what is being dated. Radiocarbon dating of OM in soils (for instance, Perrin et al., 1964) is less reliable and is subject to many poorly-understood influences (Campbell et al., 1967).

The next section will attempt to present a summary of European and North American glacial chronology, leading to a summary (II 2.3) of the late-Pleistocene glacial chronology of New Zealand, prior to a consideration (II 2.4) of evidence pertaining directly to the Franz Josef region.

II 2.2 Brief General Review of World-wide Pleistocene Glacial Chronology

This topic has been exhaustively reviewed by Charlesworth (1957) and Flint (1957, 1965), among many others. This section will attempt to condense into two tables information gathered from a wide range of literature - there will inevitably be many simplifications and omissions. Past climates were discussed by Brooks (1949) and Schwarzbach (1963).

The Quaternary Ice Age is certainly not the first on the Earth. Öpik (1958) suggested at least four previous periods of glaciation: Permo-Carboniferous, Eo-Cambrian, Algonkian and Huronian; respectively 200, 480, 750 and 1000 million years ago. Coming to the Pleistocene, Flint (1957) gave the following sequence of major Glaciations, with possible dates derived by this author from various sources:

<u>Europe (Alps)</u>	<u>Central North America</u>	<u>Years Before Present (BP)</u>
<u>Würm</u> (Main Riss/Würm (Eem)	<u>Wisconsin</u> Sangamon	(14,000- 25,000 (50,000- 70,000
<u>Riss</u> Mindel/Riss (Holstein)	<u>Illinoian</u> Yarmouth	100,000-130,000
<u>Mindel</u> Gunz/Mindel (Cromer)	<u>Kansan</u> Aftonian	180,000-220,000
<u>Gunz</u> Donau/Gunz	<u>Nebraskan</u>	260,000-330,000
<u>Donau</u>	(?)	(?)

In this scheme Glaciations are underlined, Interglacials not underlined.

Some more recent glacial and climatic events may now be collected into Table 1. Information in this Table is culled from the above references, together with Flint and Deevey (1951), Wright (1957), Movius (1960) and Burrows (unpub. table).**

** Discussion with Mr. C. Burrows, Department of Botany, University of Canterbury, on various aspects of Late-Pleistocene chronology is gratefully acknowledged.

II 2.3 General Review of Late-Pleistocene Glacial Chronology in New Zealand

This section will concentrate upon the Westland glacial sequences, and thus will exclude any consideration of North Island glaciation, and much of the South Island glacial stratigraphy in the north and east. It will be largely taken from the recent comprehensive review by Suggate (1965), which consolidated much of his previous work, as well as work by M. Gage and many others. Consequently, these workers will not be listed in the References.

Suggate (loc. cit.) (p.85) tentatively correlated New Zealand Glaciations (underlined) and Interglacials with the European sequence:

<u>New Zealand</u>	<u>Europe</u>	<u>Years BP</u> (from previous table)
<u>Otira Glaciation</u> Oturi	<u>Würm Glaciation</u> Eem	14,000- 70,000
<u>Waimea Glaciation</u> Terangi	<u>Riss Glaciation</u> Holstein	100,000-130,000
<u>Waimaunga Glaciation</u> Waiwhero	<u>Mindel Glaciation</u> Cromer	180,000-220,000
<u>Porika Glaciation</u>	<u>Gunz Glaciation</u>	260,000-330,000

On p.80 the correlations, set out here in Table 2, were given, with dates interpolated from p.84.

The Kumara region, near the mouth of the Taramakau River, Westland, is an important "type" area, as the whole or remnants of moraines and outwash surfaces of all Glaciations back to the Hohonu Advance (Waimaunga Glaciation) are present. Altitudinal and spatial

sequences may be recognised in this valley, together with correlatives in the Grey and Hokitika valleys to the north and south. Reasonably complete shore-lines, representing the high sea-level transgressions of the Terangi and Oturi Interglacials, are also present near Hokitika and inland from Greymouth. Fig. 22 (in Suggate, 1965) showed the limits of ice advances and old shore-lines in North Westland. Fig. 23, showing the Pleistocene deposits of the Kumara region, is especially instructive. A portion of the Legend to Fig. 23 is reproduced in Table 3, to be read in conjunction with Table 2.

Before considering the glacial chronology of the Franz Josef region, it is necessary to mention the occurrence of some minor glacial advances since the Late-Glacial began with the retreat from the Kumara-3 (K_3) moraines. An advance of the Franz Josef Glacier, considerably smaller than the K_3 and correlatives, produced a perfect lobate moraine about 200' high with a single crest 2-3 miles west of Franz Josef Glacier township. It is called the Waiho Loop, and is almost certainly a correlative of the Birch Hill moraine in the Tasman Valley (Speight; 1961, 1963), and the Valders and Salpausselkä moraines in North America and Scandinavia. Its age is therefore likely to be a little less than 11,000 years. Some doubt may exist regarding this correlation; S89/- (5120 ± 140 years BP) is a peat sample from a kettlehole on the Birch Hill Moraine, and represents a minimum age for the surface. It has been suggested (anon.) that Birch Hill, Waiho Loop and Rapahoe Terrace (near Greymouth) (NZ13 = 4720 years BP) are correlatives, but proof is lacking and the former correlation (Birch Hill-Salpausselkä-Valders-Waiho Loop)

is most likely. After the deposition of these moraines the glaciers withdrew uncertain, but considerable, distances. Nevertheless, small advances left minor moraines: in the lower Waiho Valley (see II 2.4), and in the Ben Ohau Range, South Canterbury.* McGregor's correlations are, briefly:

<u>Ben Ohau Formation</u>	(Dun Fiunary member (Jack's Stream member (Ferintosh member	"probably less than 1000 years old" correlative (?) of "oldest post-climatic optimum" in Alaska and Utah. About 3000 years old.
<u>Hypsithermal</u>		(see Table 1; from perhaps 4,500 to 7,500 years BP)
<u>Birch Hill II</u>		
<u>Birch Hill I</u>	(a little more recent than 8460 ± 120 years BP)	Contemporaneous with the Cockburn Glacial Phase (Cochrane Moraine in northern Canada)

* V. McGregor, 1966; (manuscript in press) "Holocene Moraines and Rock Glaciers in the Central Ben Ohau Range, South Canterbury, New Zealand". Details from D.B. Lawrence letter to C. Burrows, 13 June, 1966.

II 2.4

Late-Glacial Geochronology
of the Franz Josef Region

The aim of this section is to examine the evidence relating to glacial advances and retreats in this region, with particular reference to the areas selected for pedological study. Although such a discussion might more properly be placed in the "Materials and Methods" Chapter (III), it is more logical to complete the above brief Review of Pleistocene geochronology (II 2.2 and 2.3) at this point in the thesis. Reference should be made to Figures 6 and 7 and to Table 7 for geographical and pedological details of the Franz Josef soils studied by this author.

It is obviously very desirable to date land surfaces accurately for a Chronosequence study. Younger surfaces should be dated most accurately, as rates of change of soil properties are greatest in young soils, and it is fortunate that historical evidence is often available for the last century, to supplement other methods. As apparent steady-states of various components are achieved, and as rates of change of seral vegetation associations diminish, so the necessity for accurate dating becomes less imperative.

There are relatively few sources of information about glacial retreat of the Franz Josef Glacier, despite the fact that its fluctuations during the last century are better documented than any other New Zealand glacier. The information upon which the following analysis is made may be itemised:

1. Fluctuations during the last century were recorded by workers such as J. von Haast, A.P. Harper,

(R1902/10) <100 years BP) Organic carbon from
 surface mineral soil
 horizon - Okarito*

5. Correlation with glacial sequences further north
 (see II 2.3).

Youngest surfaces - less than 100 years of age

Stevens (1963) deduced the ages of the six youngest surfaces (0, 6, 12, 25, 45 and 55 years at the time of sampling for Stages I - VI inclusive), and no information has been presented to refute or significantly alter these. Ages of shrubs (derived by D.B. Lawrence) largely confirm them, making allowance for variable but small (2-4 years) periods of ecesis. The area immediately north of Peter Pool (so named by von Haast in 1876) is probably about 10 years older than the area immediately south of the Pool, which is shown supporting a Carmichaelia sp. association approximately 10-15 years old in a photograph in Harper (1894). Thus, Peter Pool existed about 90 years ago, and the adjacent area to the north is about 10 years older. Stage VII is therefore about 100 years of age.

Older surfaces - up to 1000 years of age

Little evidence is available with regard to the precise ages of these surfaces. The "key" date is 1750 AD, representing the probable maximum advance of the Franz Josef Glacier in recent centuries (Gunn, 1956). D.B. Lawrence (pers.comm.) dated a Podocarpus totara on the top of Cone Rock, Fox Glacier valley, tilted at the maximum advance of the Fox Glacier in 1749 AD. Other glaciers - the Nigardsbre in Norway and Eliot Glacier on Mt. Hood,

* See "Materials and Methods" (III), and Table 7, for details of this soil.

Oregon - advanced to maxima in 1748 AD and 1740 AD respectively (Lawrence, pers.comm.), and it seems entirely reasonable that the Fox and Franz Josef Glaciers were synchronous. Lawrence and Lawrence (1965) showed on a photograph the approximate position of the Franz Josef terminal face at this time. The log dated at 1690 ± 60 years, deposited in the lower part of outwash 5ch. downstream of the 1750 AD moraine, probably represents the beginning of deposition between a maximum of 2000 and a minimum of 200 years ago, but its stratigraphic relationships are not very clear. Nevertheless, the upper surface of the outwash is probably the same age as Stage X, on the criteria of vegetation, degree of soil development and altitude, and will therefore be older than 200 years of age. Organic C in the upper mineral soil horizon of Stage X, Pit One, (289 ± 36 years BP) gives the absolute minimum age for Stage X, which will undoubtedly be rather older than 300, but younger than perhaps 1000, years of age. Further evidence is lacking, and Stage X will be regarded as 500 years old.

The 1750 AD advance pushed a moraine ridge hard against the up-valley side of the Stage X outwash surface, which is about 70' above the Waiho River. Outwash from or during this advance probably formed the terraces on east and west sides of Stage X, on one of which Stage IX is found, about 40' above the Waiho River. This would indicate that Stage IX is perhaps 200 years old, but this author is reluctant to believe that the observed differences in the vegetation between Stage VII (Griselinia littoralis some 30' high, with no kamahi) and Stage IX (large kamahi and rata 80' high and 2-3' in

diameter) could arise in only 100 years. On the other hand, the vegetation is not as old on Stage IX as on Stage X. An estimate between 200 and perhaps 300 years is indicated; Stage IX will be regarded as 250 years of age.

One other surface, Lower Wombat, is found near the mouth of the Waiho Valley, 80' above the Waiho River. It is younger than terminal moraines 4,500 years old (Gunn, 1956) one mile south of the Alpine Fault, since it undercuts the foot of one of them. It is probably constructed from material previously part of the outwash surfaces further up-valley, and thus must be much less than 2000 years of age. It is definitely older than Stage IX, and probably a little older than Stage X, since it is slightly higher above the Waiho River and supports a greater proportion of large trees than Stage X. Radiocarbon dates of soil OM (R1902/3,/4) are no help. The age of Lower Wombat is therefore estimated at 1000 years, but with little confidence in the precision of this date.

Oldest surfaces - more than 1000 years of age

The three oldest surfaces - Upper Wombat, Mapourika and Okarito - may only be dated by correlation with other glaciations elsewhere on the West Coast. Upper Wombat is a kame terrace (ice-contact deposit) partly altered by river flow soon after deposition, with at least one infilled kettle (Lake Wombat) and a number of small (less than 50' high) kame mounds. It was produced at a late stage of retreat from the Waiho Loop (11,000 years old), while ice melted away from the valley walls. Shortly after its deposition the Glacier retreated with a minor re-advance to build the terminal moraines immediately

south of it 4,500 years ago (Gunn, 1956). Since the Glacier deposited the Waiho Loop 11,000 years ago, retreated and thinned, built the minor moraine inside the Loop, and retreated to the Alpine escarpment during the Hypsithermal and prior to 4,500 years ago, the Upper Wombat surface is not likely to be much older than 5,000 years of age. The sample S71/508 (2430 ± 35 years BP) probably dates the early stages of alluvial deposition by the Tatare Stream, and gives an unrealistic minimum age for the minor moraine inside the Loop.

The Mapourika surface is bracketed in time by the moraines on the west side of Lake Mapourika, and the Waiho Loop. These moraines, correlatives of the Kumara-3 advance (R.P. Suggate, in the Westland National Park Handbook), are approximately 14,500 years old (see Table 2), and were described by Gunn (1956). At this time, the Franz Josef Glacier extended in two lobes westward from The Mummy (see Fig. 6) past the present coastline at a slope of $3\frac{1}{2}^\circ$ (depositing the high-level moraine at 1100' a.s.l. south of the Waiho River; Wellman, 1955), and northward to terminate north of the present Lake Mapourika, leaving a similar high-level moraine at 1200' a.s.l. with a slope of 4° . The Mapourika surface is a dissected kame terrace built at a very late stage of retreat from the K_3 maximum, but older than 11,000 years by the time necessary for the Glacier to retreat some 3 miles before the small advance which built the Waiho Loop. An age of 12,000 years is estimated for this surface.

The oldest surface - Okarito - is almost certainly a correlative of the Loopline-2 deposits (later Kumara-2

advance; see Table 3), and no better estimate of its age is available than the Kamaka terrace date of $22,300 \pm 350$ years BP (NZ116). Gunn (1956) described three major stages of retreat from the maximum at this time, and the Okarito surface is sited on the oldest group of moraines, extending from Kohuamarua Bluff inland towards Lake Wahapo.

Summary

These dates, derived from evidence based on varying proportions of deduction and supposition, are obviously not all equally reliable. They are, however, all in the correct sequence and of the right order of magnitude. They are summarized below, with possible ranges in parentheses. The least reliable estimates are preceded by a question mark.

<u>Surface</u>	<u>Age</u> (years)	<u>Possible Range</u> (years)
Stage I	0	(No doubt)
Stage IV	25	(24-27)
Stage VII	100	(95-110)
Stage IX	250	(200-300)
Stage X	500	(300-?1,000)
Lower Wombat	1,000	(500-?1,500)
Upper Wombat	5,000	(4,500-?6,000)
Mapourika	12,000	(11,500-13,000)
Okarito	22,000	(20,000-22,300)

II 3. PODZOLISATION AND GLEYING

II 3.1 Introductory Review of the Occurrence of Podzols and Gleyed Soils

It is probably true to say that no soils have been studied so much as podzols, podzolic soils and gleyed soils, and consequently there has grown up a vast and frequently contradictory bibliography on the subject. Despite this continuing concentration of effort, even now there would seem to be little unanimity of opinion regarding the exact nature of podzolisation, and even less about gleying. This section will first attempt to indicate some aspects of podzols and gleyed soils in the United Kingdom, passing to a consideration of some possible mechanisms of podzolisation and gleying (II 3.2), and lastly to a brief consideration of some aspects of gley podzols in Westland, New Zealand.

An early review of the topic was written by Joffe (1949), who covered much of the Russian work. Despite the strongly edaphic orientation of his book, Russell (1950) dealt at some length with the podzol and podzolisation, together with the effects of impeded drainage and groundwater on soils. An excellent review by Muir (1961) traced the historical confusion inherent in the literature of the subject. Lastly, Franklin (1962) reviewed aspects of podzols and peats prior to a study of these soils and their integrades.* Much of the following discussion will be taken without specific reference from these four reviews.

* Syn: intergrades.

The term 'podzol' is derived from the Russian peasant word 'zola', signifying the apparent widespread connection within Russia of whitish infertile soil layers underlying recent ashes produced by shifting cultivation. Indeed, for a long time, the term podzol was applied only to this bleached layer, irrespective of lower horizons, and without appreciation of illuviation as a feature of podzols. 'Gley' (Russian:glei) is a popular Russian term describing a compact subsoil of greenish-blue colour commonly found near swamps or seepages. Vysotski first introduced the term to pedological literature in 1905 (Crompton, unpub. notes). Podzols are normally formed under an acid, mor litter, in freely drained PM's under moist and cool conditions (with a considerable excess of rainfall over evapotranspiration) - the processes of podzolisation are dominated by climate. Podzols are thus usually Zonal soils, unlike gleyed soils, wherein the gley features may often be the result of poor drainage conditioned by topographic features. The processes of podzolisation are in general enhanced by acidic or quartz-rich PM's poor in bases and of coarse texture, and by a coniferous vegetation giving an acid mor litter, but the effects of Climate, PM and Biotic Factor are inter-related and modify each other, so that podzols may be found under broadleaved trees in Fiordland (Wright and Miller, 1952), or in the tropics on siliceous PM's under heath (Klinge, 1965). Conversely, despite a cool moist climate and acid litter, podzolisation may be negligible on base- or clay-rich PM (Robinson et al., 1949). Since the degree of horizon differentiation evidenced in podzols is usually considerable they are considered mature soils, best formed on stable landsurfaces of low relief after the lapse of

considerable periods of time since the initiation of soil formation.

Because the morphology of podzol profiles is so variable from place to place it is not easy to outline the features of a typical podzol. However, a Universal Podzol (in the Aristotelian sense) may perhaps be reconstructed, detailing many of the features common to most podzols. In addition, Table 4, collated from many sources, compares and contrasts prominent features of podzols and gleyed soils. A Universal Podzol might be:

- | | | |
|----------|--------------|---|
| A_{00} | (L) | thick mat of undecomposed litter, loose, fibrous |
| A_0 | (FH) | decomposing litter, mor-like, matted, many fungal hyphae, sharp boundary to |
| A_1 | | perhaps 15cm brownish sandy loam to loam; slightly sticky; weakly developed medium crumb structure; low permeability; no mottles or concretions; many roots; sharp boundary to |
| A_2 | | perhaps 20cm pale grey sand; firm and sometimes cemented; massive, or weakly developed fine platy structure; moderate to low permeability; no mottles but sometimes a few small ferruginous concretions near the base; few roots; diffuse boundary to |
| B_1 | (B_h) | perhaps 15cm dark reddish-brown sandy clay loam; sticky; moderately developed medium blocky structure; moderate permeability; some diffuse reddish mottles and some ferruginous concretions; much diffuse black organic matter; few roots; indistinct boundary to |
| B_2 | (B_{fe}) | perhaps 15cm reddish-yellow sandy clay loam; sticky; moderately developed medium blocky structure; moderate permeability; many prominent reddish mottles and many |

ferruginous and manganiferous concretions;
little organic matter; few roots; very
diffuse boundary to

B₃ (B_{al}) yellowish sandy loam; friable; weakly
developed fine blocky structure; moderate
permeability; few mottles or concretions; no
visible organic matter; no roots; very
diffuse boundary to

C weakly-weathering parent material.

Wide variations from this hypothetical modal profile are likely - certain horizons may be poorly developed, and horizon nomenclature and properties may differ considerably from the above. An incomplete selection from the literature on podzols might include the series of studies on normal soils of New York (for example, McCaleb, 1954), details of podzols in Russia (Rode, 1964), Colorado (Johnson and Cline, 1965), and New York (McFee and Stone, 1965), and the properties of an iron pan humic podzol from Newfoundland (McKeague et al., 1967). In particular, the next few pages of this thesis will discuss hydrologic sequences of podzols, gleyed soils and their variants described by workers in the United Kingdom such as R. Glentworth, E. Crompton and C.B. Crampton.

One of the first to differentiate between podzol variants was Frosterus (quoted by Russell, 1950; p.537), who showed how a well-drained iron podzol may be converted first to an iron-humus podzol and then to a humus podzol as the water table rises. Muir et al. (1940) were able to map many such sequences, and presented much chemical data. Glentworth and Dion (1949) confirmed this work and added to the chemical data for soils of Aberdeenshire, but their main contribution was their recognition of catenary hydrologic sequences which repeated themselves across the

country, and which could be utilised in mapping soils. Between four and seven distinct stages in a soil continuum passing from ridge crest to valley were described in relation to drainage status. The concept has been extended by Crompton (1952, 1956) and Crampton (1963, 1965a). These four papers form the basis of the following notes, together with Figure 1, which is closely patterned after a figure on p.212 in Crampton (1965a).

It will be clear from Figure 1 that topography governs the balance between the rates of lateral and vertical water movement (flushing and leaching), and thereby affects the balance between gleying and podzolisation. The soils may be discussed in relation to Points 1 to 6, ascending the slope.

Point 1. Deep peaty gleyed soil on drift, or peat over gley. These soils are permanently waterlogged, and the gley rarely exhibits any mottling. Towards the foot of the slope the peat thins, and bright ochreous mottling (possibly of lepidocrocite) may occur in old root channels within the gley. The soil then changes to

Point 2. Iron pan podzol, or podzol with gleying. Here, a humic horizon overlies 'prisms' of imperfectly drained soil, surrounded by freely-drained soil with a thin iron pan (possibly of goethite) at the interface (see Crampton, 1963, p.286). The core of the cup-shaped prism is anaerobic due to saturation by the overlying waterlogged humic layer. The freely-drained eluvial horizon overlies a freely-drained illuvial horizon, over weathering rock. This soil occupies regions of rapid change of slope, at Points 2 and 4, but upslope of each Point somewhat different soils are found.

Point 3. Podzolised sol brun acide. This is a relatively uncomplicated soil possessing an organic A_1 over a freely-drained illuvial B (sometimes with an eluvial A_2), over weathering rock. It is likely that lateral flushing would be active within the B horizon. As the slope decreases the podzol with gleying reappears (Point 4), which then changes to

Point 5. Peaty gleyed podzol. Here the organic horizon is thicker and more frequently saturated, and it overlies a deep eluvial gleyed horizon, as at Point 1. However, Point 5 differs from Point 1 in that a freely-drained illuvial horizon is present below the gleyed eluvial layer (above the weathering rock), and a thin iron pan is formed at the junction of eluvial and illuvial horizons. In effect, the cup-shaped prisms of the podzol with gleying have become continuous horizons. The thin iron pan is best developed in light-textured materials, and may degrade into a band of strong mottling in heavy-textured soils. Crompton (1956) described the appearance of the thin iron pan:

"Wherever it occurs, the thin iron pan has its own characteristic morphology. The lower half of the pan is dark brown to bright orange brown, and the upper half is black and metallic in appearance, often overlain by a mat of roots."

Clearly, it is the result of eluviation of iron from the A_2 horizon, which invariably has a high SiO_2/Fe_2O_3 ratio in the clay fraction. At least two explanations of its development have been postulated. The first, and least satisfactory, is that the pan is the result of normal processes of podzolisation, in which iron is eluviated from the A_2 horizon and deposited in the B_1 or B_2 . This supposedly produces an impermeable and continuous pan

which impedes downward water movement, leading to gleying in the A_2 . In other words, podzolisation is the necessary precursor of gleying. Such a process is no doubt possible and may well occur, but does not account for cases where the pan is not continuous, nor for soils in which the iron pan is the only visible form of iron accumulation, an unlikely occurrence in podzols. The second and most satisfactory explanation (Crompton, 1952, 1956; Franklin, 1962) is based upon the invariable presence in these profiles of two particular features: a very acid, greasy, peaty surface layer saturated with water most of the year, and a comparatively freely-draining subsoil. This theory is supported by the occurrence in some soils (Franklin, loc. cit.) of another thin iron pan between F and H horizons - in this case inverted with the brown surface above and black below, presumably produced by anaerobic saturation of H and A_2 horizons, giving ferrous compounds which are oxidised intermittently as the F horizon occasionally dries out. The second explanation does not require podzolisation to precede gleying. Upslope of the peaty gleyed podzol lies

Point 6. Shallow peaty gleyed soil on rock, similar to Point 1.

Wilde (1946) has defined Gley soils as:

"Soils in which the gley layer occurs within the reach of the main root system of trees or cultivated plants...are classified as gley soils."

He presented (p.49) the following generalised morphology:

A_0 - Dark to black partly decomposed organic remains, often of peat-like nature.

- A₁ - Nearly black layer with infiltrated humus.
- A₂ - Light-coloured, podzolic or podzol-like leached layer, sometimes with mottling by ferrous iron and other reduced compounds.
- B - Brown or greyish-brown accumulative horizon enriched in sesquioxides; often not present.
- G₁ - Mottled, bluish-grey, rusty, bluish-brown, ochreous or humus-ochreous gley.
- G₂ - Greenish or bluish, wet or moist, deoxidised gley layer, impoverished in iron and somewhat enriched in colloidal silica.

Wilde recognised three basic variants of gley soils - alpha, beta and gamma (shallow, mid and deep) gley soils - based on the depth to the gley layer from the surface. The above profile is evidently a beta or gamma gley, which Crompton (see below) would regard as a Ground-Water Gley.

Crompton (unpub. notes) has made a useful distinction between Surface-Water (S.W.) Gleys and Ground-Water (G.W.) Gleys, the former caused by the relative impermeability of some part of the profile itself, and the latter associated with the saturation of the profile from below by regional groundwater or perched water table. On these criteria, the peaty gleyed podzol is the result of S.W. gleying (beneath a saturated humus layer), while the gley podzol is attributed to G.W. gleying (topographic rise in water table). They are thus quite distinct. If for no other reason, the distinction between S.W. and G.W. gleying is valuable in governing different approaches to artificial drainage. Finally, Franklin (loc. cit.) has pointed out that the hydrologic sequence outlined above is most commonly distributed in space (from valley to crest), but may also be encountered in the same soil evolving in Time.

II 3.2

Possible Mechanisms of
Podzolisation and Gleying

Any attempt to explain the processes of podzolisation and gleying must answer the rhetorical questions: "How are organic and inorganic constituents mobilised in upper, eluvial horizons of podzols?", and "How are they immobilised in lower, illuvial horizons?" This section will attempt to summarise some of the concepts and hypotheses about these processes which have at various times held sway in pedological literature. The above two questions - especially the second - are still very much unresolved. In addition, this section must also mention in passing some aspects of the fate of phosphorus in podzolised and gleyed soils, and something of the dynamics of these processes in soils.

Podzolisation

The topic was reviewed at some length by Joffe (1949), with particular emphasis on Mattson's theory of isoelectric precipitation. This theory postulated that basic colloidal humic and sesquioxide groups were mobilised in A horizons as the pH decreased there, were transported to B horizons, and precipitated at the respective isoelectric points for aluminium- (in B_3 ?), iron- (in B_2 ?), and humus-groups (in B_1 ?) as the pH increased. The theory is regarded as less plausible in the light of modern concepts of chelation, and also in view of the fact that not all podzols have higher pH levels in B horizons. Russell (1950) considered the process of podzolisation only briefly, and the next major review known to this author is that of Stobbe and

Wright (1959). Further reviews are those of Rudeforth (1963) and Crawford (1962, 1965). Stobbe and Wright's paper forms a useful starting-point for this discussion.

It is possible that sesquioxides may be mobilised and translocated as inorganic cations (Fe^{++} and Fe^{+++}); but this can occur only at very low pH, as the solubility of ferric oxide is negligible above pH 3.5. Another improbable mechanism is the formation of negatively-charged, silica-protected iron oxide sols: but it has been shown that at least thirteen parts of silica are required to peptise one part of iron oxide, and the process occurs only in alkaline solution. The possibility of hydrated free oxides being transported as negatively-charged humus-protected sols was first suggested by B. Aarnio. The humus may carry with it from three to ten times its own weight of oxides, but the theory is questioned because it demands the presence of considerable amounts of divalent cations in the B horizon to precipitate the sol. This situation rarely obtains in podzols. The most likely theories involve the formation of soluble metal-organic complexes, and/or the formation of chelates, with some portion of the organic matter providing the ligand. Chelation will be discussed first.

The recently-discovered phenomenon of chelation in biological situations has been reviewed by Mortensen (1963) and Schatz et al. (1964). Specific examples of chelation by lichens present during early stages of soil formation were given by Schatz (1963). Schatz and Schatz (1965), in a rather unconventional paper, discussed the chelating powers of various tropical plants. Duff and Webley (1959) demonstrated that some bacteria could

release calcium from insoluble salts and minerals by the production of 2-ketogluconic acid. Several workers (for example, Atkinson and Wright, 1957; Levesque and Hanna, 1966a) have used solutions of the salts of ethylenediaminetetraacetic acid (EDTA) to simulate the action of natural chelates; but Crawford (1965) was unhappy about the use in experimental pedology of such an exotic substance with an abnormally high resistance to microbial decomposition. Swindale and Jackson (1956) coined the term "cheluviation" to denote the processes of mineral decomposition by the formation of chelates in solution, and subsequent eluviation. Unfortunately, although work with known chelating agents such as EDTA has produced effects similar to those of natural organic decomposition products (see below), it is difficult to prove the presence of chelating agents and chelated complexes in soils. However, the circumstantial evidence in favour of cheluviation is strong.

It has long been known that the passage of rainwater through surface litter layers produces leachates containing stable water-soluble extracts of metal-organic complexes, although the nature of these compounds is not yet fully understood. C. Bloomfield in England, M. Schnitzer and various colleagues in Canada, and P. Lossaint in France, and many other workers, have all carried out intensive investigations in this field. Much of Bloomfield's work was reviewed by himself in 1965, and Schnitzer's series of papers "Organo-Metallic Interactions in Soils" (for example, Schnitzer and Skinner, 1965) is still continuing. Bloomfield (1953) was the first to show that plant litter extracts reduced a large part of the free ferric iron in soils to ferrous, and suggested (1957)

that the active agents which formed complexes with the ferrous iron were polyphenols. His conclusions were confirmed by Coulsen et al. (1960a), who isolated polyphenols in leaf extracts, and in the B horizon of podzolic soils (1960b). The Canadian work, on the other hand, has tended to contradict some of these conclusions. The active agent was first thought to be an acidic polysaccharide and later a compound with an acidic group (De Long and Schnitzer, and Schnitzer; quoted from Muir et al., 1964a), and the iron was thought to be in the form of a ferric oxide colloid protected by organic matter. Muir et al. (1964a+b) carried out an extensive series of fractionations and separated aqueous extracts of Scots Pine needles into 'amino-acid', 'organic-acid' and 'neutral' fractions. Seventeen amino-acids were identified, but were found largely ineffective in maintaining iron in solution above pH 4.5. On the other hand, the 'organic-acid' fraction contained phosphoric acid and three α -hydroxycarboxylic acids (citric, malic and quinic), all of which were effective mobilising agents. Whatever the nature of the active agents, all these workers have shown that rainfall leachates and/or aqueous extracts of fresh leaves from various species of tree can dissolve ferric hydroxide and prevent its precipitation from solution above pH 3 (Muir et al., 1964a). Below is the present author's summary into eight points of what appear to be the main conclusions to be drawn from Bloomfield's work.

1. Water extracts of fresh litter from many species contained large amounts of polyphenols.
2. The power to mobilise was directly correlated with polyphenol content of extracts.

3. However, in experiments with soils, more iron oxide was mobilised by weaker extracts than stronger, because of sorption of reaction products onto previously precipitated iron oxide.

4. The more iron oxide present, the more mobilised.

5. Very little iron oxide escaped from model profiles in leachates - most was immobilised in some manner.

6. All plant species tested (both so-called mor-formers and mull-formers) gave extracts which mobilised iron oxide - in fact, extracts from the litter of broadleaved ("mull-former") trees were most powerful. Therefore, factors which counteract this power to mobilise must be operative in unpodzolised soils under broadleaved species.

7. Fresh litters gave active extracts containing high molecular weight polyphenols. Ageing the litters before extraction gave extracts of low mobilising power which contained mostly low molecular weight polyphenols.

8. Humified material gave extracts of low activity - a possible explanation of point 6.

It is now necessary to examine some of the mechanisms postulated for the immobilisation in the B horizon of the translocated metal-organic complexes, or chelates. The validity of the Mattson isoelectric theory and the "divalent-cation precipitation" theory have been questioned earlier. There appear to be three possible mechanisms: ageing of the sol, microbiological attack of the humus "protection" on the sol or the organic ligand, and sorption on to ferric oxide. Stobbe and Wright (1959) mentioned several of these mechanisms, but were unable to decide upon the most likely. Muir et al. (1964b) agreed with this uncertainty:

"Deposition of iron oxide in the B horizon of podzols is not easy to explain, but it is possible the ferric hydroxide sols are involved. A change in the ratio of iron to active acid by the destruction of a part of the acid would be

sufficient to cause a ferric hydroxide sol, stabilised by the acid, to coagulate and be precipitated. A change in the concentration of the soil solution by evaporation and, probably most important of all, ageing of a ferric hydroxide sol, would cause precipitation. The nature of the soil fabric, whether surfaces are relatively fresh silicate material or free sesquioxides, would also influence precipitation. Further work, however, is required to decide how important a part these mechanisms play in the illuviation of iron."

Swindale and Jackson (1956) suggested that some of the chelating agents may lose their effectiveness with time and allow their ligand to separate from the metal. Crawford (1965) devoted some space to an experiment, and a discussion, on the problem of iron deposition. A fungus Mortierella ramanniana is persistently found in the illuvial horizons of podzols, and appeared in the "illuvial zone" of some model soil leaching experiments. On the other hand, Dommergues and Duchaufour (1965) inferred from experiments on the microbiological decomposition of ferric ammonium citrate that biological mineralisation (accumulation of iron) in the B horizon of podzols does not occur. Wright and Schnitzer (1963) decided that fulvic acid chelates of iron and aluminium were precipitated low in the profile by further reaction with the same metals, and by very small amounts of ionic Ca^{++} and/or Mg^{++} . McKeague (1966) repeated some early experiments by Bloomfield (1951), and could not confirm Bloomfield's suggestion

"that the formation of some soil horizons, pans and mottles enriched with ferric oxides might be due to the fixation and subsequent oxidation of Fe^{++} on ferric oxide surfaces".

To summarise, the situation appears confused and uncertain still. Few workers have mentioned the mechanisms involved in the mobilisation, translocation and immobilisation of aluminium, which cannot be reduced. Making a cautious choice, it seems most probable to this author at this time that mobilisation is accomplished by chelation, and immobilisation by microbiological destruction of the ligand.

Gleying

There are a number of characteristics generally associated with gleying (see Table 4), but there is often uncertainty whether they are causes or effects. It seems agreed that the creation of an oxygen deficit by water-logging and microbial activity produces a biological or non-biological anaerobic reduction of ferric and manganic compounds at a mildly acid pH. Anaerobic conditions can exist in the centres of water-saturated structural units as small as 6mm in cross-section (Greenwood, 1961). Reduced Fe and Mn (with Cr, V, Co, Ni and Ti; Brooks, 1965) diffuse towards less-saturated, aerobic regions where precipitation into mottles, concretions or ortstein occurs, by some combination of oxidation, microbiological attack or sorption. The mobilisation processes are accelerated in the presence of surface layers of plant litter. All these generalised statements have been confirmed by Bloomfield (1951) and McKeague (1965b) under experimental conditions. McKeague demonstrated that low E_h values developed in experimentally saturated soils at 1°C, where microbial activity would have been slight; but the most pronounced gleying was produced at room temperature in soils with surface litter layers.

A comprehensive discussion of gleying was made by Crampton (1962-63). After reiterating details of the hydrologic sequence of gleyed soils, podzols and their integrades (see II 3.1), he discussed the evidence relating to biological or non-biological anaerobic mobilisation of iron - the former tends to decrease pH markedly, in contrast to relatively high and constant pH under the latter condition.

Weir and Soper (1963) considered the possibility of a complex between iron, organic groups and phosphate ions. They found that carboxylic and non-carboxylic hydroxyl groups in humic acid could retain iron above pH 4.7, even against an anion resin. Nearly all the phosphate held in the complex was exchangeable with radioactive P^{32} , although little was plant-available to sunflowers. Levesque and Hanna (1966b) leached Podzol, Brown Podzolic and Grey Brown Podzolic soils with di-sodium EDTA and demonstrated a marked associated P and Fe movement in the Podzol. The loss of P in podzols and podzolic soils in the field has been traced by Wild (1961).

Two other aspects of the dynamics of podzols and gleyed soils remain to be discussed. The field-relationships of the soils outlined by C.B. Crampton and E. Crompton have been mentioned (II 3.1), and a sequence of podzolisation noted (Franzmeier et al., 1963). Methods for determining the degree of podzolisation were outlined by Tatarinov (1966). Rode (in Joffe, 1949, p.350), Franzmeier et al. (loc. cit.) and Stobbe and Wright (1959) all agreed that a "conditioning" process of base removal is necessary before podzolisation can be initiated. Presumably, this phase is represented by a degraded Brown Earth or a Sod-Podzolic (Muir, 1961). Franklin (1962)

linked this aspect with the second topic of this paragraph - lessivage - by recalling Mattson and Lönnemark's assertion that the B horizon of podzols "grows" upwards and the A horizon "grows" downwards.

"If this is so, the transition from the A to B horizon cannot be sharp except in old soils, implying that podzols must go through a podzolic or degraded brown earth stage in their evolution. This is in agreement with the theory that lessivage often or always precedes podzolisation (Duchaufour, 1951; Karpachevskii, 1960)" (from Franklin, 1962).

Lessivage (or "Illimerisation"; Fridland, 1958) is the mechanical downwards translocation of clay in colloidal form without chemical disruption. Both Duchaufour (1951) and Fridland (1958) distinguished between soils in which clay is transported unaltered ("lessive") and those in which it is disrupted ("podzolique"); but Parfenova and Yarilova (1960) disagreed on the grounds that lessivage, as well as clay decomposition, formation and movement, all occur together in nearly all soils. The only probable exceptions are sandy podzols (Rudeforth, 1963). However Rode (1964) wrote:

"Analysis of 31 profiles of Podzolic, Sodpodzolic, Light Grey, Grey and Dark-grey soils in the Soviet Union...has indicated that in the formation of the vast majorities of profiles of these soils lessivage played absolutely no essential role".

Romans (1962) ascribed the formation of indurated B₃ horizons of podzolic soils in Scotland to pedological rather than periglacial processes, but Crampton (1965b) reached the opposite conclusion for some soils in Wales.

II 3.3

Some Aspects of Gley Podzols in
Westland, New Zealand

The waterlogged counterparts of the podzolised Yellow Brown Earths and Podzols in New Zealand - the Gley Podzols or "pakihi soils" - cover 750,000 acres of easy country and 100,000 acres of hilly country in Westland, where the rainfall is usually more than 100" per annum (Taylor and Cox, 1956). Taylor and Pohlen (1962) described the iron pan in these soils as follows:

"In gley podzols (podzols with a gleyed A₂ horizon), the pan is typically thin, indurated, and high in iron, especially where the underlying layers are well aerated gravels or sands in sharp contrast with conditions occurring above".

They contrasted gley podzols with ground-water podzols, in which the pan is high in organic matter and relatively low in iron. The slope of the pan in ground-water podzols is governed by the slope of the water table, and the pan may be strongly to weakly cemented, forming what is popularly known as 'coffee rock'. Under the new classification scheme proposed by Taylor and Pohlen (loc. cit.) gley podzols are denoted 'A-gleyed iron illuvial podic soils'. Wells (1962; Data on Soil Profiles for the International Soil Conference) classified the Okarito Peaty Loam on the Aerodrome Terrace, Hokitika, (described by C.G. Vucetich) as a 'Deep Southern Gley Podzol', or a 'Deep iron illuvial A-gleyed podic soil with superimposed madenti-podic'.

With the exception of an article in "Soil News" (Cutler, 1960) there are no published descriptions of New Zealand soils similar to those of the hydrologic (hydromorphic) sequences discussed earlier (II 3.1). Cutler traced the sequence of Podzolised Yellow Brown

Earths (including gleyed variants), Gleyed Podzolised Yellow Brown Earths, Gley Podzols, Peaty Gley Podzols, and Peats over Gley, in topographic situations from rolling and hilly, undulating and concave slopes, higher flats and lower flats, to lowest areas. He discussed the effects of varying depths of humic litter on regeneration of forest species, especially rimu (Dacrydium cupressinum). From the present author's experience it is clear that hydrologic sequences very similar to those described by Crompton and Crampton are common on gently sloping knolls adjacent to pakihi swamps in Westland.

Pakihi lands, because they were relatively clear of vegetation, were early expected to provide good agricultural country; but all aspiring farmers were to be sadly disappointed. Considerable agricultural experimental work was carried out on pakihi soils at the start of the century by B.C. Aston, and T. Rigg and T.H. Easterfield of the Cawthron Institute. All their papers stressed the two major inhospitable features of the gley podzols - their infertility, and lack of lateral and vertical drainage. Recent interest in the topic has been expressed in papers by workers such as Chittenden (1965). Attempts to establish exotic forests on the intractable Okarito soils have not met with consistent success, and attention has been switched to undulating areas of other soils under lower rainfalls in North Westland. Okarito soils have for millenia supported stands of indigenous species of one kind or another (Chavasse, 1962). Widespread logging in Westland during the last century is thought to have caused a rise in the water table (a swamping process), after the manner described by Tiurin

et al. (1935). McDonald (1955) attempted to check this assumption but obtained somewhat inconclusive results, which tended to show that swamping had not occurred after logging forests on Okarito fine sandy loam soils. Topsoils had relatively high porosities but in subsoils low pore space measurements (% air space at 50cm moisture tension) of 8.9, 5.3 and 2.5 were recorded. In both topsoils and subsoils an appreciable volume of the total pore space was occupied by water at low tensions, even after dry periods of weather.

There are rather few discussions on New Zealand gley podzols in the literature. A symposium in "Soil News" (June, 1960) covered much of what was known at the time, with articles by C.G. Vucetich and L.C. Blakemore on their pedology and chemistry respectively. Burns (1931) measured pH, carbon and nitrate-N in soils under forest plots in various stages of regeneration from wasteland to mature forest, and under control plots. Low nitrate-N levels were reported, possibly due to lack of nitrifying bacteria (low pH) and consequent accumulation of ammonium-N. Thick litter layers were apparently inimical to forest regeneration, while burning decreased the thickness of the litter layers and increased pH and nitrification, and promoted successful regeneration. Harris and Harris (1939) described a number of soils in the Westport area, and recognised "bad" pakihi soils (such as the Addison series) and "good" pakihi (Sargeant soils).

The first extensive soil survey in Westland was made by H.S. Gibbs (Gibbs et al., 1950), and further information on soils of Westland may be found in Gibbs (1964). Figure 4 in the latter paper showed a sequence of

soil development in a series of monoliths, proceeding from Hokitika gravelly sand to Ikamatua sandy loam, Waiuta loam and finally Okarito peaty loam. Gibbs et al. (1950) incorrectly classified Okarito fine sandy loam as a ground-water podzol (after Robinson, 1936) - the New Zealand gley podzol is an A-gleyed soil produced by surface-water gleying beneath a saturated mor-type FH layer, and is classified as a Zonal soil in the scheme of Taylor and Cox (1956). Peat-over-gley soils are "soils of the hydrologic end of a catena" - they are ground-water gleys and thus Intrazonal soils. Brief descriptions of typical soil profiles in Gibbs' sequence leading to a gley podzol are: (taken from Gibbs et al., 1950)

RECENT SOIL

Hokitika gravelly sandy loam (near Kokatahi)

Free-draining shallow soil on alluvium under totara forest.

4 in. brown gravelly sandy loam,
on stony gravels containing some sand.

PODZOLIC SOIL - YOUNG TO IMMATURE STAGE

Ikamatua sandy loam (near Waiho)

Light, well-drained soil on alluvium under kamahi forest.

6 in. dark brown matted mor,
 3 in. brown sandy loam,
 18 in. brownish-yellow loamy fine sand,
on grey coarse sand.

PODZOLIC SOIL - SEMI-MATURE TO SUB-MATURE STAGE

Waiuta loam (near Waiuta)

Heavy, slow-draining soil on rolling slopes under rimu forest.

- 8 in. reddish-brown mor layer,
- 4 in. deep brown loam, mellow,
- 6 in. light brownish-grey fine sandy loam,
- $\frac{1}{2}$ in. rust brown iron pan,
- 12 in. deep yellow sandy clay loam, compact and showing strong orange mottling,
- on grey stony sandy loam with many yellow and orange streaks.

PODZOLIC SOIL - MATURE STAGE

Okarito fine sandy loam (near Hokitika)

Heavy, very poorly-drained soil on moraines or outwash terraces under rimu-miro-kamahi-quintinia or rimu-silver pine forest.

- 9 in. deep brown fine sandy loam, peaty and spongy,
- 8 in. pale blueish-grey silt loam, moderately compact, slight orange mottling,
- 12 in. pale yellowish-grey silt loam, slightly compact, slight orange mottling,
- 6 in. brownish-grey silt loam, slightly compact,
- on gravels, strongly cemented in the upper 4 in. and with other thin cemented layers in the gravels between three and nine feet from the surface.

These thin layers of ortstein are produced by a fluctuating water table within the fluvioglacial gravels.

Some chemical analyses for these soils were given, and are reproduced in this thesis in Table 5. Additional analyses, on Okarito peaty loam only, were given by Wells (1962). They will not be reproduced here, but some points are noted:

1. The dominant clay mineral in all horizons is illite, with considerable amounts of chlorite, interlayered chlorite and clay-vermiculite.
2. pH of dried soil in water suspension is 4.1 in the A₀ and A₁ horizons, and close to 4.8 in all other horizons.

3. CEC is 66.4 me.% in the A_0 , 30.8 in A_1 , and 15.3, 27.5, 15.6 and 21.2 in the other horizons respectively. %BS is 25 and 14 in A_0 and A_1 , but practically nil below the A_1 horizon. The dominant exchangeable cation is Ca^{++} in all horizons, including the A_2G .

4. %carbon decreases down the profile from 30.8 to 19.7, 5.2, 8.9, 4.3 and 4.0, while C/N ratios rise down the profile from 24 to 33, 43, 47, 33 and 44, with the maximum in the B_hG horizon.

5. Total P levels seem quite reasonable in most horizons (580, 210, 140, 360, 240, 380 p.p.m.). %organic P is over 50 in all horizons except the lowest, reaching about 80 in the A_0 . P extractable by 1.0N H_2SO_4 is much lower in all horizons than Inorganic P derived by subtracting Organic P (ignition method with 1.0N H_2SO_4) from Total P (HF- HNO_3 extraction), showing that considerable amounts of Inorganic P are in forms insoluble in 1.0N H_2SO_4 . P retention (5g soil shaken 24hr. with 25ml phosphate solution (1 mg/ml P) at pH 4.6) is low (12, 13 and 36%) in the top three horizons, but reaches very high levels in the lower horizons (89, 60 and 71%).

6. Tamm oxalate extractions give the following results for the six horizons:

	A_0	A_1	A_2G	B_hG	G	an B_h
aluminium %	.15	.12	.58	1.14	.53	.92
iron %	.16	.05	.02	.03	.02	.10

Some of these results do not correspond very closely with analyses in Table 5. The Okarito fine sandy loam of Table 5 was collected on the Hospital Terrace near Hokitika, while the International Soil Conference reference site was on the Aerodrome Terrace, at a slightly higher altitude.

The Okarito soils discussed above have developed within loess capping the fluvioglacial gravels - this is not the case for Okarito soils on $K_{2.2}$ surfaces in South Westland (see Chapter V in this thesis).

II 4. PODOCARP SUCCESSIONS IN NEW ZEALAND*

II 4.1 Some Features of Podocarp Forests

It is the purpose of this section to mention just a few studies on various aspects of podocarp forests in New Zealand, prior to a discussion of Holloway's Climatic Change Hypothesis, and a section specifically dealing with the Westland podocarp forests. A final section will consider the relevance of some of these ideas to a Chronosequence of soils and vegetation near the Franz Josef Glacier. A Glossary of plant names is appended after II 4.4.

At least two major points were stressed by Nicholls (1956) in his study of upland indigenous forests in Taranaki. The first was the instability and erosion-potential of the forests and soils; and the second, the lack of podocarp regeneration.

"A pronounced lack of podocarp advance growth is considered to be neither the result of linear succession nor a phase in a successional cycle, but is attributed to the effect of recent climatic variation. In the main the forest is, however, a climatic climax association developed since the final cold period of the Pleistocene" (Nicholls, 1956).

Further to the north-east, McKelvey (1955) and Cameron (1960a) commented upon natural regeneration of podocarps

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in the Whirinaki area; their general conclusion being that in certain favoured situations, with the elimination of cultural and animal interference, and with nurse manuka crops and viable disseminules, podocarp regeneration is at present possible after fire, although it may take more than a century for a viable stand to develop. Drawing on the work of Richards and Aubreville in tropical rain-forests Cameron (1954) attempted to demonstrate the operation of cyclic regeneration and mosaic formation in the Whirinaki forests. Typically, the forests have at least two tiers - the upper canopy dominants, and the seedlings of future dominants - but these seedlings (or poles) are rarely of the same species as the members of the upper canopy. The forests appear to be composed of mosaics, in which the species succeed each other cyclically with alternating dominance. Considering only 'normal' sites (those not edaphically, geologically or geographically 'abnormal'), he noted that where podocarps were dominant only hardwood (mainly tawa) poles were present, and under a tawa canopy seedlings of tawa were not normally found. Under more open kamahi and quintinia canopies regeneration of podocarps was sometimes seen. He proposed a cycle (see Figure 2), which shows some similarities to one proposed by Grant (1949). There seem to be a few anomalies, such as the appearance of young tawa (3) after old tawa (2). A trenchant commentary by J.T. Holloway was appended to the paper, and the following points were made:

1. Despite some structural similarities it is doubtful whether New Zealand forests behave like their tropical counterparts.

2. The wrong area was chosen for investigation - the Whirinaki forests are indisputably seral forests younger than 2000 years.

3. The attractive nature of the cyclic theory is belied immediately by the fact that one portion of the cycle (hardwoods back to podocarps) has not yet been satisfactorily demonstrated.

4. Such cyclic regeneration and formation of mosaics needs long periods of stable climate. Such stability does not seem to have prevailed in New Zealand, although it may obtain in tropical regions.

An interesting example of a "physiologic cycle" in Southland forests was given by Holloway (1946). Here podocarps, rata and kamahi showed variations in abundance and habit of growth, with the hardwoods forming minor associations representing phases in a major association cycle, which is illustrated in Figure 3. The heavy-boled rata and kamahi appeared to have an epiphytic origin - when tree ferns were present, rata and/or kamahi could establish only on the crowns (caudices) of the ferns, due to the intense shading of the ground. This killed the ferns, and allowed small (normal-boled) hardwoods to establish on the ground. The later death of the large hardwoods allowed sufficient light for podocarp regeneration. The large podocarps then shaded the pole hardwoods, ferns reappeared and hardwood regeneration was again only possible epiphytically.

There remain two important papers to mention in this section. The first (McKelvey, 1953), dealt with forest colonisation in West Taupo after the Taupo eruption about 200 AD. A large area was devastated and has since been rapidly colonised from the western edge towards Lake Taupo in the east. The most westward forests (podocarp-

hardwoods with a poor podocarp stocking) are the third or fourth generation, while the most eastward (dense podocarps) are the colonising generation. Colonisation did not proceed as a gradually-moving wave from the west, but was accomplished under nurse manuka (and other scrub) associations, producing large areas of even-aged forests. The hardwood content of the forest types increased from east to west, in the order

1. dense podocarps
2. scattered podocarps-maire-hinau
3. scattered podocarps-hinau-tawa
4. scattered podocarps-rata-hinau-tawa.

That is, the hardwood sere in the lowland forests is; firstly maire and kamahi, secondly hinau, thirdly tawa (or rewarewa or quintinia), and fourthly rata, which may sometimes form combines on podocarp trees. The oldest forest immediately adjacent to the pre-eruption King Country forest contains only scattered rimu as the dominant podocarp, and there are many podocarp-rata combines. There are variations on this pattern in the sub-montane and montane forests. Some dense podocarp stands occur in the far west, which seems anomalous, but is explained by the common edaphic feature of level, low-lying and previously swampy areas.

The second paper is by Robbins (1962). He described, using forest profile diagrams, twelve separate areas of podocarp-hardwood forest in the North Island. This evidence was used to support an alternative theory of plant succession, and in part to refute Holloway's hypothesis. His arguments will be discussed later (II 4.2). However, Robbins seems to have accurately, but

subjectively, described some typical North Island forests. The general conclusions were:

1. Forests with the greatest podocarp component are always the youngest, whereas older forests show a dominant hardwood element.
2. Rimu is the most ubiquitous podocarp, has the greatest timber volume, and five times the abundance of any other podocarp. Matai and totara dominate on recent soils such as dry terraces and basins, and on the forest margins. Totara is a frequent 'pioneer' within the podocarp seral sequence.
3. Podocarp stocking may vary from 60 stems/acre (young forests) to virtually nil (old), with pronounced structural variations. "Thus, all cumulative evidence points to a decline in time of the podocarp element accompanied by a subsequent increase in the broadleaf element". He could not correlate this with changes of soil, climate or topography in the present habitat.

II 4.2

The Climatic Change Hypothesis

The development of Holloway's Climatic Change Hypothesis may be traced in five papers dealing with Southland podocarp-beech forests (1946, 1947, 1948, 1950, 1953). The forests fall into three general formations:

1. Podocarp-hardwood forests of the coastal margins with temperate oceanic climates.
2. Beech forests of inland regions with sub-continental climates.
3. Beech forests of regions with mountain climates.

There are major changes in species distribution taking place.

"Near the coast silver beech invades and replaces podocarp forest. Inland, the more xerophytic mountain beech replaces silver beech, only to be replaced in turn by scrublands and grasslands" (1948).

The last paper (1953) dealt with the condition of the logged podocarp stands of the Longwood Range. A dismal picture was painted: virtually complete failure of podocarp regeneration following logging, the development of scrub hardwood stands dominated by fuchsia, and eventual dominance by unmerchantable kamahi. Rata, previously a co-subdominant with kamahi under a podocarp upper canopy, appeared to be eliminated after logging. Only on the most favourable sites (deep, free crumb-structured silt or sandy silt loams with warm and sheltered aspect) did podocarps show signs of regenerating. Evidence of this nature led to the theory that the podocarps are out of phase with present regional climates - they are relict from a warmer, more humid, climate.

At the same time, and independently, Raeside (1948) described certain anomalies in some soils of the Canterbury Plains and Downs, and North Otago mountains. These could only be accounted for by assuming there had been a change in the ambient climate less than a millenium ago, to conditions cooler and drier than during the first thousand years AD. Many peculiarities and anomalies in the structure and behaviour of many South Island forests may be explained in terms of this hypothesis.

"The forests as a whole are in an unstable condition consequent on comparatively recent changes in regional climates...."
(Holloway, 1954a).

He gave many examples of situations explicable in terms of this hypothesis, although he did not at any time say there could be no other explanation. The general effect of the hypothesised climatic change was to limit podocarp regeneration in many areas from about 1300 AD, allowing the formation of forests containing a disproportionate number of even-aged and over-mature trees. It should be realised that the change has not killed the established podocarps, but has merely prevented their regeneration. This process cannot be correlated with any edaphic or geographic factor save climate. A point of contention has been the degree of cultural interference by the Maori, in his use of fire. Cumberland (in McCaskill, 1962), in a harsh and intemperate attack, disputed many aspects of the hypothesis and ascribed the large-scale devastation of forests, especially in the central and eastern South Island, solely to anthropogenic factors. Holloway (1964)

answered this attack and refuted many of Cumberland's accusations, repeating that the forests, although in many cases actually destroyed by fire, were already in a condition to be destroyed, without ready regeneration.

Robbins (1962) disputed aspects of the hypothesis, and his paper bears examination, despite the somewhat cursory treatment Holloway gave it (1964). Dr Cockayne, who noted the regeneration failure and general decadence of many podocarp forests, invoked the classical plant succession theories of linear seral processes, whereby the podocarps were a sub-climax association, due to be replaced by various hardwood species as a climax. This is perhaps permissible when applied to one locality, but he failed to account for the widespread nature of the process. It is inconceivable that all the podocarp forests in New Zealand are of an age where they are just proceeding to the climactic hardwood stage. Another theory is that of mosaic or cyclical regeneration, which was discussed earlier. Holloway's hypothesis offers the most satisfactory explanation for all the many forest anomalies so far observed, and evades the error Cockayne made. Robbins, however, postulated the "Broadleaf Forest Dominance Hypothesis", whereby

"...the true nature of the present forests is presented as a vast historical fusion between an older, purely Gymnospermous forest which pioneered in the recolonisation of the post-glacial landscape, and a subsequent invading dicotylous broadleaf forest which is only now gaining the ascendancy. While the present pattern stems from the post-glacial habitat readjustment, the origin of both forests can be traced back into pre-glacial time".

Robbins' specific criticisms of Holloway's hypothesis included:

1. He considered Holloway incorrect in saying that the forest changes should be less pronounced in the North Island, as the climatic range would not be so critical; which appears a rather minor point and one on which Holloway was not dogmatic.
2. He found it very difficult to deduce the exact "modus operandi" of the climatic change - the way in which it actually affected the podocarps. In view of the fact that Holloway did not propose actual changes countrywise in terms of so many degrees temperature or inches of rain, the criticism is a little premature. The crux of the argument is that the podocarps, due to the combined effects of fire and less favourable climates, were not able to regenerate successfully.
3. He observed ancient rimu-rata combines, and prominent podzolisation under already ancient tawa forests, and attempted to refute the dating of the climatic change in the North Island, which was thought to be ca. 1500-1600 AD. Robbins' evidence apparently pointed to a long-term progressive and irreversible decline of the podocarp element, rather than a momentary and possibly reversible alteration.

The essence of the Robbins hypothesis is that 'competition' (complex interactions and inter-relations of differences in growth rates, life spans and maturity heights) is invoked, in that the replacement of podocarps is inevitable because the broadleaved trees are in the "evolutionary ascendancy", just as the rise of the

Angiosperms over the Gymnosperms since the Cretaceous is demonstrable in pollen studies. At this moment there is a transition, in which both groups are almost equally suited to the environment but where the broadleaved species are slightly superior competitors, hence their advance where practicable. The greater podocarp decline in the North Island, according to Robbins, is thus explicable in terms of a greater competitive effect of a larger number of broadleaved species, with more "autecological potential". Failure of podocarp regeneration is simply ascribed to shading and other competitive effects by the fast-growing, rapidly-dispersing broadleaved species.

It would seem that facts rather than theories are now needed, and Dr P. Wardle appears to be one of the few independent spirits collecting and assessing information. Wardle and Mark (1956) noted examples of podocarp degeneration, such as log remains of Hall's totara and pink pine, and described the advance of silver beech near Dunedin. In the Hokitika catchment (1960) he noted over-mature, dead or dying kaikawaka and pink pine, with no middle-aged trees but some recent regeneration, which may indicate that conditions are again becoming favourable for podocarps. A similar situation was seen near Kaikoura (1961), where a possible very recent amelioration of climate may allow establishment of totara, matai and kahikatea, but probably not rimu. This may correlate with the widespread deglaciation during the last century. Again (1962), the upward and outward extension of silver beech and upward contraction in the range of pink pine all add weight to the climatic change hypothesis. A study on Secretary Island (1963a) also

showed a gap in rimu regeneration, although, disconcertingly, regeneration appeared to have continued even into the 17th Century. The summary of another paper (1963b) is reproduced entire here, as it admirably summarises the situation:

"The majority of stands of Dacrydium cupressinum, Podocarpus spicatus and Libocedrus bidwillii at six localities in the South Island and Stewart Island show a "regeneration gap", i.e., a paucity of seedlings, saplings, and young trees. This is most evident to the east of the Main Divide, and least evident in Stewart Island. Increment borings indicate that the lowest rate of regeneration occurred between 1600 and 1800 A.D., if it is assumed that the growth rings are annual. It is suggested that during this time, the area supporting regeneration contracted into the coolest, moistest and least drought-prone parts of the country, and that more recently, it has been expanding again. This is in fair agreement with Holloway's hypothesis concerning the effects of climatic change on South Island forests."

II 4.3

The Westland Podocarp Forests

It is now possible to turn our attention to the published work dealing specifically with Westland's forests.* It is intended to present first an overall account of the features and successions of the terrace forests, and then a discussion of two papers by Poole (1937) and Grant (1949).

The general structure of the terrace forests has been well described by Foweraker. Under the dominant podocarp tier of rimu, with some miro and occasionally kahikatea, there is a broadleaf tier containing mostly kamahi and quintinia, and all or any of the following broadleaved species: horoeka (lancewood), kapuka (Broadleaf), mahoe, pate, toro, porokaiwhiri, hinau, pokaka, putaputaweta and (rarely below 800' a.s.l.) Southern rata. This mid-canopy overlies shrubs (mostly Coprosma spp.), which in turn covers a ground tier of ferns and herbs. The general impression given by Foweraker and Hutchinson in their papers is that podocarp regeneration was quite widespread, with a forest composed of many even-aged groups, not necessarily mature or over-mature. They probably paid too much attention to the prevalence of large blow-downs with subsequent active regeneration. Moreover, there was no doubt in their minds that the podocarp facies is

"the final or climax type on practically all parts of the morainic terrace areas"
(Hutchinson, 1931b).

* Cockayne; 1928: Foweraker; 1925, 1929: Hutchinson; 1928, 1929, 1931a, 1931b: Kennedy; 1954, 1961: Chavasse; 1954, 1962: Holloway; 1954a, 1954b.

The forests may be roughly classified in the following manner (Holloway, Chavasse and others):

1. Mountain protection forest east of the Alpine Fault: a few over-mature and senescent rimu and a strong rata-kamahi element. Hall's totara and kaikawaka are found at higher altitudes, and some miro at lower altitudes, where also the rimu tends to be more vigorous.

2. Hill forests west of the Alpine Fault: well-drained terrace slopes with mature podocarps and a strong broadleaved element.

3. Terrace forests: dense rimu with some miro and kahikatea, a greater proportion of silver pine, kaikawaka and occasionally other Dacrydium species on the boggier areas. There is a shrubby understory of broadleaved species.

4. Flood-plain forests: matai-totara on well-drained areas, and kahikatea on wetter areas.

5. A collection of other forest types of local significance. These include coastal forests and scrub, forests on consolidated sand-dunes, type variants induced by edaphic or geologic anomalies, and forests showing ancient or recent cultural interference.

It is of interest to discuss the successions which may have operated over the last millenium. Previous to the hypothesised climatic change it is postulated that the mountains and drier hill areas (groups 1 and 2 above) carried vigorous and regenerating podocarp forest, dominated by rimu and miro, with rata and kamahi as sub-dominants. The lowland terraces (3) had bogs and swamps of varying degrees of acidity, infertility and wetness. The most acid areas carried bog vegetation with some silver pine and kaikawaka, and less acid areas probably supported kahikatea, but the situation was a highly complex patchwork of forest types. With the onset of cooler and drier conditions rapid colonisation of these

areas took place as the bogs became progressively drier. Podocarp regeneration ceased under the more severe climate of the mountains. Thus, the terrace forests of even-aged semi-mature podocarp forest are probably not much older than about 800 years. The successions envisaged are these:

On acidic bog soils

Peripheral invasion by manuka, then silver pine and sometimes kaikawaka (kahikatea on least acid soils), and then rimu. The probable succession is then an increasing preponderance of rata-kamahi or kamahi-quintinia - presumably relatively permanent in the absence of beech, which replaces it in Southland.

On swamp soils

First nigger-heads, peripheral invasion by flax, thence various Coprosma and other shrubby species, and finally dense kahikatea stands. There is some evidence that these are stable under the present climate, but it is possible that rimu, and finally broadleaved species, may invade and oust the kahikatea.

On recent alluvial soils

Previously podocarps (totara, matai, kahikatea) were forest colonisers on these areas, but nowadays new ground is often pioneered by a wide range of shrubby hardwood species, with suppression of podocarps. On areas covered by wandering rivers, principally in the far south of Westland, kahikatea may colonise youngest surfaces very rapidly, and as the stands age they become progressively restricted by the onset of podzolisation, passing through stages of tall dense kahikatea to old scattered kahikatea

to rare veteran kahikatea over young rimu, and eventually to rimu forest or possibly decadent rimu with silver pine (Chavassee, 1962).

To summarise: at the climatic change the hill and mountain rimu stands stagnated and rata-kamahahi assumed dominance. At the same time rimu was able to spread across the warmer low-altitude bogs, now becoming slightly drier. Colonisation was rapid but very patchy and uneven, and the most recalcitrant pakihi soils remain unforested due to infertility or wetness. Decreasing soil fertility in areas marginal to pakihi may prevent the apparently inevitable progression to hardwoods from podocarps, and the encroachment of beech from north and south. There has not yet been enough time for this to be resolved.

An area of forest near the Wanganui River (Pukekura State Forest) was described and discussed by Poole (1937). The main association over the whole area, except the very badly-drained portions, is rimu-kamahahi-quintinia. Hilly areas contain degenerate podocarps with epiphytes, and a prominent rata-kamahahi element. There are a few pakihi with silver pine, and also a small area of kahikatea. The rimu-kamahahi-quintinia association was considered the climax community in equilibrium with its environment. The individual members are undergoing a definite series of life cycles, which in their various stages bring about frequent and abrupt physiognomical changes in the forest - a grouping phenomenon. Poole described the cycles thus:

Starting from a mature stand of rimu (up to 30" d.b.h., 120' height, straight boles, bunched crown in the last 30'), with straight 60' kamahahi and quintinia:

1. Gradual opening of the canopy through windthrow and decay of all dominants in the mature stand.

2. A scrubby association of kamahi and quintinia develops to 40' height.
3. The canopy opens and rimu regenerates from sparse to profuse.
4. The rimu grows slender and straight under a fairly open canopy of the broadleaved species.
5. Passing through the canopy growth accelerates and pyramidal crowns develop. If the stocking is high a dense canopy of rimu develops.
6. Quintinia and kamahi are partially suppressed to scattered large trees with suckers.
7. Rimu matures, casts the side branches and forms a small bunched crown in the upper 30'.
8. These gradually open and decay, and the cycle continues.

Further south, at Saltwater Forest, Grant (1949) wrote at length about this kamahi-quintinia cycle, and other successional trends. He presented a conjectural diagram, shown here in Figure 4. Despite some inconsistencies it seems a logical and quite satisfactory attempt to depict a rather complex situation. Grant also noted the failure of podocarp regeneration on the hill and mountain slopes. On the semi-basin and basin sites of the terraces he proposed a seral succession, shown here in Figure 5. His major conclusion was

"...the plant climax for the area will be a purely broadleaf community consisting essentially in certain areas of kamahi, and in other areas of kamahi and quintinia. No definite proof of this statement exists, but available evidence favours this trend."

II 4.4 The Relevance of Synecological Studies
to a Chronosequence of Soils and
Vegetation near the Franz Josef Glacier

Several points should be borne in mind a propos this topic:

1. Vegetal changes are not necessarily correlated with, related to or contemporaneous with soil changes. It has been shown that climate is the major agent which produces striking and abrupt changes in community structure and status.
2. The ecological evidence concerning podocarp successions still appears rather confused.
3. The terraces west of the Alpine Fault have been uniformly colonised by uniformly rather young forests.
4. No definite climax has yet developed in these terrace forests, nor probably ever will, as such attainment requires long periods of climatic stability.
5. Two "successions" appear to have operated in this area:

(a) On river-flats and terraces the soils are derived from water-sorted glacial debris. There is a primary succession through Carmichaelia, Olearia, Broadleaf, and thence to rata-kamahī on the latest major terminal moraine within the valley of the Franz Josef Glacier. Chavassee (1962) proposed a totara-kahikatea-rimu-hardwood (or perhaps totara-kahikatea-rimu-silver pine) linear succession on these outwash areas: a "forward"

progression presumably due to decreasing fertility and increasing degree of podzolisation.**

(b) The High Glacial Terraces, which comprise much of Westland, appear to have undergone a "backward" succession:**

- (i) The retreat of the piedmont glacier (K_2 , about 20,000 years BP) left a confused landsurface with kettleholes and other morainic manifestations. The impermeability of the morainic material, and the topography, favoured formation of lakes, ponds, swamps and bogs, and a tundra vegetation was dominant under the wet and cold periglacial climate.
- (ii) With time, soil degradation occurred. Later, a bog-forest association developed under a warm (but still wet) climate.
- (iii) Only recently have podocarps colonised, by which time soils have already become infertile. Rising water tables after logging may prevent podocarp regeneration and the pakihis will increase in area, despite any future climatic amelioration.

6. Therefore, point 5b outlines a "backward" succession from a state of relative infertility to a possible hardwood climax, as opposed to a "forward" primary succession (point 5a) from virgin and very young fertile soils to the same hardwood climax. This climax, if it will at any time exist, has not yet been reached due to insufficient time for its formation.

** The terms "backward" and "forward" do not denote a retrogression or reversal in succession, or return to a previous stage; but are merely convenient terms to describe the situations outlined in point 5 and summarised in point 6.

Following Stage VI (see II 5.), the succession on alluvial and outwash surfaces could therefore logically be:

- VI - canopy of Olearia and dying Carmichaelia, seedling Broadleaf.
- VII - canopy of dying Olearia and dead Carmichaelia, seedling Broadleaf.
- VIII - canopy of Broadleaf over dead Olearia, entry of kamahi and/or rata.
- IX - canopy of kamahi and/or rata of medium size.
- X - canopy of large kamahi and/or rata, entry of podocarp seedlings.
- XI - same canopy, larger and more mature trees, growth of podocarps.
- XII - canopy of co-dominant kamahi and podocarps.
- XIII - healthy podocarp canopy above closed Tier II hardwood canopy.
- XIV - isolated emergent over-mature podocarps over open hardwood canopy.

This differs slightly from 5a above. In passing to morainic High Glacial Terraces (5b above) from alluvial surfaces, the succession is broken. A mosaic of pakihi areas (under rimu-silver pine) and level terraces (under youthful rimu-hardwoods) occurs apparently without relation to degree of soil impoverishment. Such situations do not represent a continuation of the linear succession of vegetation, although the underlying soils may still represent stages in a continuum of soil development - a Chronosequence.

GLOSSARY OF PLANT NAMES*

Podocarp species.

Kahikatea	<u>Podocarpus</u> <u>dacrydioides</u> A. Rich.
Kaikawaka	<u>Libocedrus</u> <u>bidwillii</u> Hook.f.
Matai	<u>Podocarpus</u> <u>spicatus</u> R.Br. ex Mirbel
Miro	<u>Podocarpus</u> <u>ferrugineus</u> G.Benn. ex Don
Pink pine	<u>Dacrydium</u> <u>biforme</u> (Hook.) Pilger
Rimu	<u>Dacrydium</u> <u>cupressinum</u> Lamb
Silver pine	<u>Dacrydium</u> <u>colensoi</u> Hook.
Totara (true)	<u>Podocarpus</u> <u>totara</u> G.Benn. ex Don
Totara (Hall's)	<u>Podocarpus</u> <u>hallii</u> Kirk.

Beech species.

Mountain beech	<u>Nothofagus</u> <u>solandri</u> var <u>cliffortioides</u> (Hook.f.) Poole
Silver beech	<u>Nothofagus</u> <u>menziesii</u> (Hook.f.) Oerst.

Hardwoods (broadleaved dicotylous species), and others.

Broadleaf (kapuka)	<u>Griselinia</u> <u>littoralis</u> Raoul
Carmichaelia	<u>Carmichaelia</u> <u>grandiflora</u> (Benth.) Hook.f.
Flax	<u>Phormium</u> <u>tenax</u> Forst.
Fuchsia	<u>Fuchsia</u> <u>excorticata</u> (J.R. & G. Forst.) Linn.f.
Hinau	<u>Elaeocarpus</u> <u>dentatus</u> (J.R. & G. Forst.) Vahl.
Horoeka (lancewood)	<u>Pseudopanax</u> <u>crassifolium</u> (Sol. ex A.Cunn.) C.Koch
Kamahi	<u>Weinmannia</u> <u>racemosa</u> Linn.f.
Mahoe	<u>Melicytus</u> <u>ramiflorus</u> J.R. & G. Forst.
Maire	<u>Gymnelaea</u> spp. (Hook.f.) L.Johnson
Manuka	<u>Leptospermum</u> <u>scoparium</u> J.R. & G. Forst.
Nigger heads	<u>Carex</u> <u>secta</u>
Olearia	<u>Olearia</u> <u>avicenniaefolia</u> (Raoul) Hook.f.

*Footnote on next page.

Pate	<u>Schefflera digitata</u> J.R. & G. Forst.
Pokaka	<u>Elaeocarpus hookerianus</u> Raoul
Porokaiwhiri	<u>Hedycarya arborea</u> J.R. & G. Forst.
Putaputaweta	<u>Carpodetus serratus</u> J.R. & G. Forst.
Quintinia	<u>Quintinia acutifolia</u> Kirk
Rata (Northern)	<u>Metrosideros robusta</u> A.Cunn.
Rata (Southern)	<u>Metrosideros umbellata</u> Cav.
Rewarewa	<u>Knightia excelsa</u> R.Br.
Tawa	<u>Beilschmiedia tawa</u> (A.Cunn.) Benth.
Toro	<u>Myrsine salicina</u> Hew. ex Hook.f.
Tree-ferns.. commonly	<u>Cyathea dealbata</u> <u>Cyathea smithii</u> <u>Dicksonia squarrosa</u>

* After A.L. Poole, N.M. Adams; 1963; "Trees and Shrubs of New Zealand"; Government Printer, New Zealand. (With the exception of Carex secta and three tree-ferns.)

II 5. A PREVIOUS STUDY OF A CHRONOSEQUENCE OF SOILS AND VEGETATION NEAR THE FRANZ JOSEF GLACIER

II 5.1

Introduction

The next few pages will review the salient points in a study by Stevens (1963), some of which were repeated in Stevens (1964). The study formed part of the requirements for the degree of Master of Agricultural Science in the University of Canterbury, and also proved to be an investigation preliminary to the more comprehensive studies reported in the present thesis.

The rapid retreat of the Franz Josef Glacier over the last half-century produced large amounts of morainic debris, subsequently fashioned into a series of alluvial terraces 0, 6, 12, 25, 45 and 55 years of age. The terraces were colonised by a succession of different plant associations, which initiated and influenced the concomitant development of a sequence of six very youthful soils. The major morphological feature of soil development was the progressive accumulation of organic matter (OM) in the upper few centimetres of mineral soil, and on the surface as a deep, fibrous, greasy, brown mor.

II 5.2 Biotic Factor and Plant Succession

The prisere on young fluvioglacial surfaces near the Franz Josef Glacier was studied in detail by T.R. Detwyler, Fulbright Scholar at the University of Otago in 1961, who generously provided much of the information on this topic reported in the thesis. He derived plant densities by species for individual communities using the Cottham and Curtis (1956) point-centred quarter method. The number of plants per hectare within three strata (0-25cm, 25-200cm, 200-800cm) are reported below; division by 10^4 gives the number of stems per square metre. Perhaps the most satisfactory manner in which to summarise the ecological data presented by Stevens (1963) is to reproduce verbatim a section from Stevens (1964).

"The 'Stages' (denoted by Roman numerals) show the following succession, but only a few key species are mentioned, with their densities.

0 Stage I: The surface is quite devoid of macro-organisms, and is bare exposed parent material at 'time zero'.

6 Stage II: The vegetation is distributed extremely discontinuously, and large areas are virtually unaltered from Stage I. There are many clumps of green Racomitrium moss, which may collect wind-blown silt; and the red-coloured alga Trentepohlia iolithus (Chlorophyceae) is very common on all rocks. The most common vascular plant is Raoulia tenuicaulis, with lesser numbers of Epilobium glabellum, E. pedunculare and Poa novae-zealandiae. The legume Carmichaelia grandiflora, which is to be so important in this prisere, makes its appearance with less than 4000 stems per hectare, all smaller than 25cm.

15 Stage III: The lower stratum has an estimated moss cover of 20%, and there is much Raoulia and large numbers of the two Epilobium species. Many seedlings (125,000) of Olearia avicenniaefolia are present in the lowest stratum and closely associated with Carmichaelia (26,000), their

vigour being directly proportional to their radial distance from the Carmichaelia. Between 25 and 200cm there are 12,000 Carmichaelia plants per hectare, and 1,300 of Olearia. Few plants are taller than one metre.

Stage IV: The vegetation grows uniformly to a height of about two metres, and is not so discontinuous as on Stage III. The lower stratum contains some Carmichaelia (49,000), and quite vigorous seedlings of Coprosma rugosa and Olearia. The middle stratum is characterised by Carmichaelia (27,000), Coprosma (12,000) and Olearia (6,000), while the tallest plants are less abundant: Coprosma (2,200), Carmichaelia (800) and Olearia (1,500).

Stage V: This Stage marks the beginning of the elimination of Carmichaelia. There are virtually no plants of this species in the lower and middle strata, and only 5,000 in the upper stratum, which is now about 5 metres tall. Olearia is not regenerating very vigorously either, although it still constitutes more than half the stems in the upper stratum (15,000 out of 29,000). Coprosma is very common in all three strata (12,000, 17,000 and 6,000). The dominants of later communities, such as broadleaf (Griselinia littoralis) and Coprosma lucida, are appearing in the lower stratum.

Stage VI: This process is accentuated through Stage VI, with upper stratum dominance by Olearia, which is not regenerating. Griselinia littoralis is becoming common (7,000 and 4,000 in the lower and middle strata respectively), and Carmichaelia is nearly absent below 200cm, with only 3000 senescent plants in the upper stratum. There are no other (proven and undisputed) N-fixers taking its place. Thus, after only 55 years the scrub is about 7 metres high, rather dense, and many mosses, ferns and hepatics are present. The situation is utterly unlike that obtaining in Stages I, II and III."

II 5.3

Results

The ecosystems on each of the six Stages were sampled by digging three large (metre-square) soil pits 33cm deep, after removing all vegetation and fresh surface litter from within the metre-square. It was divided where possible into four portions:

Living vegetation and roots, recent litter (V)
 Mor humus layer (FH)
 Upper layer of humus-enriched mineral soil,
 usually less than 10cm deep (Upper horizon)
 Lower layer of little-altered parent material
 (Lower horizon)

Mineral soil material smaller than $\frac{1}{4}$ " was sieved and weighed in the field, sieved through a 2mm mesh after drying, and volume-weights of soil less than 2mm were calculated. Reaction was determined in 1:2.5 soil-water suspensions (1:5 for V and FH); organic carbon determined by a modified Schollenberger-Allison procedure (Metson, 1956); nitrogen by semi-micro Kjeldahl digestion and distillation; and total P (P_t) and inorganic P (P_a) by the ignition method used by Walker and Adams (1958), organic P (P_o) being calculated by difference. P in V and FH was determined by the method of Kitson and Mellon (1944). Results presented below are all mean values of data from the three pits on any one Stage. Only a small selection from the original data is given here.

On such a bouldery PM volume-weights of mineral soil were rather variable, but Stages II, III, V and VI clustered around 90 kg/m^2 . Weights of OM in the FH rose from 1.2 kg/m^2 to 2.0 kg/m^2 from Stage IV to Stage VI, while weights of V rose from nil on Stage I to 8.4 kg/m^2 on Stage VI. Soil reaction dropped sharply from 7.9 in

Stage I (PM) to 4.9 in an Upper horizon of Stage VI. Starting from very low values of less than 0.1 kg/m^2 in Stage I, the ecosystem after 55 years contained 5.8 kg/m^2 of organic C, more than half of which was in the V. The average rate of accumulation was about $0.1 \text{ kg/m}^2/\text{annum}$, and no "apparent steady-state" had been reached.

Similarly, N accumulated in the ecosystem at a rate of $3.3 \text{ g/m}^2/\text{annum}$, with a maximum rate of accretion between Stages II and IV (where Carmichaelia grandiflora is the dominant plant) of nearly $7.0 \text{ g/m}^2/\text{annum}$. Nett nitrogen accretion was 160 g/m^2 (from 9 to 169 g/m^2), only a quarter of which was in the V. Again, no steady-state was apparent. An estimate of N-fixation by Coriaria arborea (a nodulated non-legume) revealed an accumulation-rate about twice that of Carmichaelia. The $\%P_o$ of P_t increased from 2.2% in Stage I to (in Stage VI) 6.2 in Upper+Lower horizons, 10.0 in Upper+Lower+FH, and 14.3 in the whole ecosystem, assuming that all P in the V was organic. FH layers contained up to 60% of their P_t as P_o . C:N: P_o ratios of Upper+Lower+FH changed from 105:10:1.22 in Stage I to 74:10:1.56 in Stage III (under dominant Carmichaelia), thence to 177:10:0.47 in Stage VI (under dominant Olearia). These changes were even more spectacular in the whole ecosystem: the C:N: P_o ratio of Stage VI was 347:10:0.54. C/N ratios of soil (Upper+Lower+FH) therefore widened from 10.5 to 17.7 (I to VI), and from 10.5 to 34.7 in the ecosystem. C/ P_o ratios in soil likewise changed from 86 (Stage I) to 26 and 44 (II and III), to 375 in Stage VI.

II 5.4

Discussion

The major change in soil morphology between Stage I and Stage VI was the addition of OM to FH and Upper horizons. Therefore, only a few soil characteristics likely to be correlated with and affected by OM - volume-weight, loss-on-ignition, pH, organic C, N and organic P - were investigated. At least two important points emerged from the field and laboratory studies: the elimination of Carmichaelia grandiflora (the only known N-fixer) from the succession soon after Stage VI; and the lack of any apparent steady-states in the accumulation of organic C, N and organic P.

By Stage V, and on older surfaces not sampled during this particular study, Carmichaelia was failing to regenerate. No other known leguminous or non-leguminous N-fixer enters the succession at any subsequent time. This bears a close resemblance to the "transition" stage of elimination of Alnus (and other N-fixers) from successions on deglaciated terrain in Alaska (see II 1.3). The advent and growth of N-fixing plants in the early stages of a sequence of soil and plant co-development is of the utmost importance to the speed and direction of this co-development. An hypothesis based on competition for phosphorus (Walker and Adams, 1958) has been put forward to explain the disappearance of N-fixers in such a sequence. Although it was most likely that competition for light was an exceptionally important factor in causing the regenerative inability of Carmichaelia, the study tended to substantiate the hypothesis. The proportion of P_o in the P_t rose to only 10% at Stage VI in the soil, but was probably much higher in the finest fractions of

mineral matter, from which the plants would initially take their phosphorus. If the coarser fractions of the mineral matter were not weathering fast enough to replenish the easily-available phosphorus supply, some measure of phosphorus starvation might be evident in plants on Stage VI. The %P in V dropped from 0.07% in the early Stages to 0.04% in Stage VI, and C/P_o ratios widened considerably by Stage VI. Moreover, any plant seedling in Stage VI must establish in the thick blanket of FH overlying the soil, and this material contained at least 60% of its phosphorus in the organic form. Since the amount of N in the ecosystem is the "hinge" around which plant growth revolves, the ultimate potential development of an ecosystem is dependent upon its nitrogen content. This should be dependent upon the growth and survival of N-fixing plants, in turn dependent upon the amount of P originally present in the PM and the rate at which this is converted to the organic, and less-available, forms.

The study revealed no diminution at Stage VI in the rate of accretion of N, and yet the principal source of N - the Carmichaelia - was being eliminated. The author stressed the importance of continuing the work, especially to determine whether the ecosystem nitrogen content increased further, in the absence of any macro-N-fixer. Any further extension of the Chronosequence could only be carried out after the recognition of surfaces older than Stage VI, whose ages could be determined with reasonable accuracy. As before, only surfaces on which the four Soil Forming Factors other than Time - Climate, Biotic Factor, Relief and Parent Material - could be kept constant or ineffectively varying, would be chosen.

III

MATERIALS AND METHODS

III 1. INTRODUCTION

Having now reviewed some aspects of the study of Chronosequences, it is necessary to discuss in detail the methods employed in the present investigation. This section begins with a statement of the general principles of site selection, followed by a short description of the reconnaissance and selection of sampling sites. There are also summaries of the major environmental and pedological features of the sequence, and the climatic data for Franz Josef. Parts III 3. and III 4. deal respectively with sampling and sample preparation, and analytical methods.

A critical examination of the extent to which four of the five soil forming factors have been kept constant or ineffectively varying is held over until the Discussion (V 1.).

III 2. PRELIMINARY FIELD WORK

III 2.1 General Principles of Site Selection

When considering the suitability of any area for inclusion in the Chronosequence the following criteria were applied subjectively:

1. The area should be level or only slightly sloping.
2. There should have been the least possible interference by man and beast.
3. The area should not be so close to adjacent slopes that it might directly gain or lose soil material, nutrients or water from or to those slopes.
4. The Parent Material of the soil should be a mixture of schists and greywacke in "intermediate" proportions.
5. The plant community, measured subjectively, should approximate to one of the stages discussed earlier (II 4.4).
6. The soil profile should not have been altered during the recent or distant past by additions of alluvium or colluvium subsequent to the original deposition from river or Glacier, unless such additions are so deep that the present vegetation is wholly rooted in them.
7. It should be possible to determine the approximate or exact age of the surface.

III 2.2

Reconnaissance and Selection

Two sets of base maps were used for the reconnaissance of the region, together with many aerial photographs.

1. Map of Westland and Mount Cook National Parks (N.Z.M.S. 180) at a scale of 1" = 126ch.
2. National Forest Survey maps S71/1 (Gibbs), S71/2 (Lake Mapourika), S71/4 (Omoeroa), S71/5 (Waiho Gorge) and S63/8 (Okarito); together with S70/9 (Cook River) and S71/7 (Weheka) for the Fox Glacier region.

Figures 6 and 7 (drawn from these maps and other sources) show the areas visited at least once during the reconnaissance of the Franz Josef Valley and Waiho River system. A number of areas near the Fox Glacier were also closely inspected, but were excluded from further serious consideration because of the lack of background information about the soils, landscape chronology and botany of the whole region. Many areas near Franz Josef were rejected when they did not comply with the above seven criteria, the most common reasons being intermittent deposition of sands and silts from the Waiho River, and extensive interference by cattle. Eventually, the areas shown in solid-black on the figures were selected for further investigation, and a set of preliminary soil samples (non-volume-weight "grab samples") collected to assess the probable range of soil properties throughout the sequence, and to test whether chemical data confirmed the sequence selected on geographical, pedological and botanical criteria. The soils were air-dried, passed through a 2mm sieve (material remaining on the sieve discarded), and analysed by methods described later

(III 4.1) except that pH was measured on decanted solutions one hour after shaking for 12 hours, and organic carbon determined by the modified Schollenberger-Allison method used previously (II 5.5). The results are shown in Table 6.

Despite incomplete sampling certain broad trends can be observed and interpreted qualitatively. These may be summarized as follows:

1. Decreasing pH with age. The pH in upper horizons decreases earlier, and falls to lower levels, than in lower horizons.
2. The %org.C and %N appear to rise and later fall. The %org.C of lower horizons increases with age.
3. C/N ratios widen considerably with age. Although Lower Wombat (30+) seems anomolous, there is a general increase with age in the C/N ratio of the lowest horizon of each soil.
4. With the exception of Stage X (0-10), P_t falls fairly consistently in upper horizons throughout the sequence, while % P_o increases to very high levels. % P_o of lower horizons also increases but at a slower rate and to a lesser extent.

After further field exploration and soil surveying, two pit sites on each surface were chosen and the soils sampled, as will be described in III 3.1 and III 3.2. They were rarely very close to the sources of the preliminary samples. Appendix I contains full descriptions of the soils in the Chronosequence, and Table 7 summarises their principal environmental and

pedological features. Throughout the rest of this thesis any given soil will be referred to in one of the following terms:

Examples of soil terminology

LW	=	Lower Wombat
LW 1.	=	Lower Wombat, Pit One
LW 1.3	=	Lower Wombat, Pit One, Third Horizon
LW 1.L	=	Lower Wombat, Pit One, L Horizon
LW 1.FH	=	Lower Wombat, Pit One, FH Horizon

This usage is extended to any discussion of soils from the first six Stages (see II 5.).

Table 8 gives a summary of climatic data for the town of Franz Josef Glacier.* As an example of the not unusual variations from these climatic means, the rainfall experienced during part of January, 1967 was:**

9.00am	Sat.	21 Jan.-	9.00am	Sun.	22 Jan.	=	8.80"
9.00am	Sun.	22 Jan.-	9.00am	Mon.	23 Jan.	=	2.47"
9.00am	Mon.	23 Jan.-	9.00am	Tues.	24 Jan.	=	9.87"
9.00am	Tues.	24 Jan.-	9.00am	Wed.	25 Jan.	=	5.46"

with a total for this month of 37.99", or more than double the long-term mean for January.

* Grateful thanks are extended to Mr. N.G. Robertson, Assistant Director (Climatology), New Zealand Meteorological Service, for providing this information.

** Figures supplied by Mr. A.J. Ure, Ranger, Westland National Park.

III 3. SAMPLING AND SAMPLE PREPARATION

III 3.1

Pit Site Location

"The Pit sites were not randomly chosen; selection was entirely subjective and was guided by two basic principles:

1. That an effort should be made to sample only areas with an "intermediate" composition of boulders and fine materials....

2. That maximum variability of vegetal material between Pits within any Stage be attempted, considering always the need for uniformity of PM...." (Stevens, 1963).

The present extension of this earlier work demanded a somewhat different approach to the problem of pit site location. In most cases it was very hard to determine the nature of the PM without digging a very deep hole (exploratory pit), and on the older surfaces it was impossible to reach the PM. Only a limited number of exploratory pits could be excavated, and obviously-aberrant pits were not persisted with. Pits were sited clear of apparent irregularities such as small eskers and piles of moraine. Secondly, as there was no attempt to sample vegetation in these later studies of the Franz Josef Chronosequence, it was necessary to select areas distant from roots and tree buttresses. Where trees grow closely together the pits were sited as far from each tree as possible. No attempt was made to apply criteria such as those of Harradine and Jenny (1958), as these were often inapplicable to this situation.

Further complications were encountered. For example, the above criteria (III 2.1) necessitated careful exploration of the LW surface, in order to avoid the

Scylla and Charybdis of a hill to the west and a scarp to the east, only 100 yards apart, together with a track, stream and stream deposits passing along this narrow terrace. A similar problem was faced at Mapourika.

During an exploration of the Okarito region it was realised that areas with zero slope were almost invariably flooded to the surface. A profile near Okarito is:

1.5m dark brown fibrous peat ("gyttja")
on 1.0m blueish-grey sandy silt, very firm and
structureless.

Thus, Ok soils were sampled on five and ten degree slopes, where there were soils with normal ABC profiles.

An additional problem was most clearly presented on the UW surface, where it was common to see intertwining surface roots entirely covering the ground, precluding any meaningful soil sampling. These areas tended to show much surface water, even though comparatively dry beneath. If this sequence is intended to reveal the pedogenesis of the Zonal soil (Taylor and Cox, 1956) of the area (a gley podzol), then areas of normal PM and normal drainage must be examined, and these cannot exclude the typically wet soils under the dense forests. However, UW 1. and UW 2. were dug on the crest of an adjacent gentle ridge, lacking these completely saturated conditions. Similar compromises were made in a number of cases.

III 3.2

Sampling Procedure

Pits VII 1. and VII 2. were sampled in the manner described earlier (Stevens, 1963), except that gravels, stones and boulders were weighed. The procedure was then changed slightly, because it proved impossible to field-sieve ($\pm \frac{1}{4}$ ") the older soils with their higher clay contents, especially when wet. Figure 8 illustrates a completed pit.

The new procedure used for all soils from IX to Ok inclusive was as follows:

The exact site for any pit was chosen from a number of exploratory pits, one of which was then deepened to perhaps a metre. One side was smoothed to form a vertical profile about 80cm wide. A collapsible wooden frame with internal dimensions of 66x66cm, enclosing four-ninths of a square metre, was then laid on the ground with the internal edge of one side above the top of the profile. This side was then removed. Any living vegetation, usually ferns and herbs, was removed with a sharp knife and packaged in polyethylene bags. The litter (L) was then carefully scraped off the surface, baring the FH, and packaged separately. Likewise, the FH was removed and bagged. The lower boundary of this layer was usually clearly distinguishable in the exposed profile of the exploratory pit. Next, each mineral soil horizon was removed in turn with a spade, trowel and small crowbar, until the arbitrary depth of 75cm, or the water table, was reached. Some boundaries between horizons were arbitrary, but most were clearly recognised. Contamination of one horizon by material from another was carefully avoided.

All material removed from any one horizon was placed on to a large square canvas sheet with brass eyelets at each corner, and most stones larger than about 1" sorted to another sheet. Most of the roots were removed at this stage. When a sufficient pile of material had accumulated on either canvas sheet it was weighed at field moisture with milk scales (graduated in 0.1lb to 60lb) hung from a nearby branch. The separates were termed "stones" and "multiple-fractions". After thorough mixing the "multiple-fractions" were spread thinly over the canvas, marked in a grid pattern, and a sub-sample of about 10% by weight taken with a stainless steel scoop and placed on a third canvas. In this manner the horizon was excavated with a level floor, and "stones" and "multiple-fractions" were discarded after sub-sampling. Eventually all sub-samples on the third canvas were carefully mixed, one or two aliquots accurately weighed into a gallon billy, and sealed in plastic bags.

Most of the profile descriptions (Appendix I) were made soon after sampling, but the photographs (Plates 1-8) required much frustrating experimentation to achieve satisfactory results. For those contemplating similar photography a short description of the procedure is given in Appendix II.

In some pits, non-volume-weight "grab-samples" were collected from the lowest horizon, using a trowel or hands. This was necessary where inflowing water prevented sampling with the care outlined above, or (in the case of VII 1.3 and VII 2.3) where volume-weight sampling had not been extended to below the depth of 50cm on an earlier occasion.

In addition, three "grab-samples" were collected one, two and three metres below an Okarito profile in a road cutting near Okarito township.

III 3.3

Sample Preparation

- (i) Green vegetation: Dried to constant weight at c. 40°C
- (ii) Litter (L): Dried to constant weight at c. 40°C, ground in a Christy & Norris mill, and a portion stored in glass screw-top jars
- (iii) FH material: Dried to constant weight at c. 40°C, ground in a Christy & Norris mill, and a portion stored in glass screw-top jars
- (iv) Roots: Dried to constant weight at c. 40°C
- (v) Mineral soils: The various "multiple-fractions" aliquots were thoroughly air-dried and sieved through $\frac{1}{4}$ " and 2mm square-hole sieves, giving four fractions of mineral matter, referred to hereafter as

Stones:	>1")	
Coarse gravel:	1"- $\frac{1}{4}$ ")	Air-dry (AD)
Fine gravel:	$\frac{1}{4}$ "-2mm)	fractions
Fines:	<2mm)	

The AD volume-weight of any fraction in any horizon was calculated from the formula

$$\text{AD fraction (kg/m}^2\text{)} = \text{AD fraction (kg)} \times \frac{\text{lb "multiple-fractions" weighed in field}}{\text{lb "multiple-fractions" aliquot weighed in field}} \times \frac{9}{4}$$

Most "stones" from any horizon were sorted by hand in the field and discarded after weighing. This figure was converted to kg/m² and added to the volume-weight of stones calculated as above. In cases where an aliquot was taken in the field from the "stones", the volume-weight of

AD stones was derived as above and added to the volume-weight of stones separated from the "multiple-fraction" aliquots.

When a "grab-sample" was collected it was air-dried, sieved to separate the four fractions and the percentage of fines calculated. The total AD volume-weight (kg/m^2) of the horizon above was divided by its depth (cm), and multiplied by the percentage of fines in the "grab-sample". This figure (assumed to represent kg/m^2 fines per centimetre for the grab-sampled horizon) was then multiplied by the depth of the grab-sampled horizon. No weights of stones, coarse gravel or fine gravel are reported for these horizons (VII 1.3, VII 2.3, X 1.6, M 1.6, M 2.5, Ok 1.5).

All mineral soils were milled (Christy & Norris Junior with 0.8mm sieve plate), and later ground by hand in an agate mortar to pass a 100-mesh sieve. Thus, three samples were prepared, termed hereafter

fines	-	less than 2mm
milled soil	-	less than approximately 60-mesh
ground soil	-	less than 100-mesh

In order to study the fate of elements within stones and coarse and fine gravels, as they weathered and disintegrated to form fines, 32 of the soils were selected (see III 4.2), the stones and gravels bulked in the calculated proportions, and finely ground to pass a 100-mesh sieve in a Tema Mill. These will be referred to as "composite samples".

Some clay samples were prepared from a few soils by shaking approximately 50g of fines overnight with deionised water containing a few ml of 0.880 ammonia,

decanting the silt+clay suspension into large glass tanks, and evaporating the clay suspension over a water-bath after settling for 24 hours and siphoning from the top half of the tank.

III 4. ANALYTICAL PROCEDURES

III 4.1

Analytical Methods

Nearly all determinations were made in duplicate.

- (i) Reaction: On fines and FH. Soil/distilled water suspensions (1:2.5 for mineral soils, 1:5 for FH) were hand-stirred intermittently over four hours, and the mean of four readings taken, using a Radiometer pH meter with glass-calomel electrodes.
- (ii) Dry Matter and Loss-on-Ignition: On milled soil. DM was determined on small (approximately 6g) samples in porcelain crucibles dried overnight at 105°C. This sample was then brought to 550°C and ignited for 1 hour to determine LOI%.
- (iii) Mechanical Analysis: On fines. The International pipette method (Imperial Bureau, 1933) was used. OM was removed by boiling gently in 30% H_2O_2 (capryl alcohol as an antifoament). Carbonates and iron coatings were removed with 0.2N HCl, and chlorides washed out on Hartley funnel filters. Coarse sand was then separated on an 85-mesh sieve, dried and weighed. The fine sand, silt and clay were shaken for 16 hours in 600ml distilled water using Calgon (commercial sodium hexametaphosphate) and Na_2CO_3 as dispersants. Silt+clay and clay samples were pipetted from 10cm depth in a litre cylinder at the appropriate times read from a table of sedimentation rates, dried and weighed. Fine sand was separated by repeated decantation after sedimentation in straight-side beakers, dried and weighed.

- (iv) Carbon: On milled soil, L and FH. The Walkley-Black wet oxidation by $1.0N$ $K_2Cr_2O_7$ and conc. H_2SO_4 was used, followed by a titration with $0.4N$ ferrous ammonium sulphate. All results are reported as oxidisable carbon, because no factor was used to convert to total organic carbon.
- (v) Nitrogen: On milled soil, L and FH. The semi-micro Kjeldahl method using a selenium catalyst was employed (Metson, 1956).
- (vi) Cation Exchange Capacity, Total Exchangeable Bases
Exchangeable Ca, Mg, K and Na; and $CaCO_3$ ** On fines and FH. Soil in leaching tubes was presoaked and then leached with neutral $1.0N$ ammonium acetate, distilled and C.E.C. determined on the ammonia collected in boric acid. Exchangeable K, Na and Ca were determined by flame photometer in a portion of the leachate, and another aliquot was evaporated, muffled, taken up in $0.1N$ HCl and back-titrated with NaOH to give T.E.B. Two further titrations with EDTA gave exchangeable Ca and exchangeable Ca+Mg. Carbonates were determined by Collins Calcimeter.
- (vii) Multiple Regressions between C.E.C., %oxid.C and %clay of various combinations of young and old soils and upper and lower horizons were derived by an IBM 1620 computer using a program prepared by

** Grateful thanks are due to Mr. P.N. Hughes, Chemical Services Department, Lincoln College, who carried out the cation exchange analyses on mineral soils; and to Mr. D.E. McNaughton, Soil Science Department, Lincoln College, who determined the cation exchange data on FH material, and performed some $Ca CO_3$ analyses.

Miss M. Mathieson (Agricultural Economics Research Unit, Lincoln College) and with the help at various times of Dr. N.J. Peet (Department of Chemical Engineering, University of Canterbury) and Mr. C.A. Yandle (Agricultural Economics Department, Lincoln College).

- (viii) Total Analyses for K, Ca, Mg, Fe, and P. On ground soil and "composite samples". Small samples (usually 0.200g) were intimately mixed with 2.000g of AR Na_2CO_3 and fused over a Mekker burner in platinum or Palau crucibles. The melt was extracted with 9N HCl or H_2SO_4 , filtered after digesting on a water bath, and made to 250ml. L and FH samples were digested in a ternary acid mixture (10HNO_3 - $1\text{H}_2\text{SO}_4$ - 4HClO_4) essentially according to Jackson (1958, p.331). Appropriate aliquots were taken for separate K, Ca and Mg determinations by flame photometer for K, and Techtron AA-2 atomic absorption spectrophotometer for Ca and Mg (in HCl solution), using SrCl_2 (1000p.p.m.) as a suppressant. Iron was determined by a modified Jackson (1958) procedure, using an acetate buffer, hydroxylamine hydrochloride, and orthophenanthroline. The colour was read at 512m μ on a Uvispek spectrophotometer. Erratic and unpredictable differences as large as 500% between duplicate fusions sometimes occurred, despite perfect duplication between these same extracts in P, Ca, Mg and K analyses. This problem is discussed later (IV 4.). The method of Kitson and Mellon (1944) (vanadomolybdophosphoric acid yellow) was used to determine P in the L and FH digests, and the Fogg and Wilkinson (1958)

(reduced ascorbic acid) method for all other P analyses. In the former method the colour was read at 470 m μ , and in the latter at 825m μ . Attempts were made to determine total Al in fusion extracts using Aluminon (Lindsay, Peech and Clark, 1959; Hsu, 1963; and various modifications of those) and with the atomic absorption spectrophotometer, but without consistent success.

- (ix) Tamm Extractions of Fe and Al: On the "selected soils" (see III 4.2) and some clay separates. The method used by Saunders (1965) was adapted for centrifugation. Milled soils were used, as the use of fines would have led to large sub-sampling errors. Samples (1.5g) were twice shaken for 1 hour with 50ml of ammonium oxalate-oxalic acid extractant, centrifuged and supernatants removed. Extracts were evaporated to low volume, digested with conc. HNO₃ and later 1+1 HNO₃ and HClO₄, evaporated and baked, taken up in 1+1 HCl, filtered and made to a convenient volume. The method described above (viii) was used to determine iron. Aluminium was determined by two EDTA complexometric titrations, using a method developed by the New Zealand Soil Bureau.** An excess of 0.05M EDTA was added to suitable aliquots of extract, neutralised to methyl red, sodium acetate buffer added and the solutions boiled gently for 3 minutes. After adding 90% ethanol the solutions

** The valuable assistance of Mr. L.C. Blakemore, Soil Bureau, D.S.I.R., in solving some difficulties with this method is much appreciated.

were rapidly cooled to below 10°C in a deep freeze and titrated with 0.02M zinc acetate to a permanent violet using Eriochrome T in triethanolamine and methanol. The Al-EDTA complex was destroyed by adding saturated sodium fluoride, the solutions boiled once more, cooled and again titrated to determine the EDTA released from the complex.

- (x) Organic Phosphorus: On milled soil. The ignition method described previously (Stevens, 1963; Walker and Adams, 1958) was used, except that P was determined by the method of Fogg and Wilkinson (1958).
- (xi) Inorganic Phosphorus Fractionation: On milled samples of the "selected soils". The method of Williams (1965) and Williams et al. (1967) was used with some minor changes. This method is a much-modified version of the original Chang and Jackson (1957) and Glenn et al. (1959) fractionation schemes, and at one stage incorporates a simultaneous replicate extraction by NH_4F and $\text{NH}_4\text{F}+\text{P}$ to correct for resorption of P from solution during extraction. Essentially it consists of sequential extractions of a sample (1.000g) by repeatedly adding extractant, shaking, centrifuging, taking an aliquot, removing supernatant and drying. A flow sheet is given in Table 9. P is determined in most extracts by the method of Dickman and Bray (1940), in the citrate-dithionite extract by the method of Watanabe and Olsen (1962), and in the Na_2CO_3 fusion extract by the method of Fogg and Wilkinson (1958).

- (xii) X-Ray Diffraction Patterns: Slide-mounts of sands, silts and clays from fines of six horizons were prepared by Mr. A.S. Campbell, Department of Soil Science, Lincoln College, using conventional methods. They were subjected to XRD analysis by Mn-filtered FeK α radiation at 40KV and 20ma from a Phillips X-Ray spectrometer. K-saturated clay samples were then heated to 500°C and re-examined, and another set was Mg- and glycerol-saturated. The results are primarily qualitative, and quantitative deductions must be made with care.

III 4.2

The 32 "Selected Soils"

After performing analyses on all soil samples for pH, mechanical composition, oxidisable C, N, Total P by fusion, total and organic P by the ignition method, and C.E.C., and calculating volume-weights of gross soil separates, an attempt was made to select 32 mineral soil horizons for more detailed examination. The criteria were largely subjective and difficult to apply consistently. Soils with "grab-sample" horizons were avoided if possible, as were soils with apparently aberrant volume-weights of fines. Selection was frequently complicated by soils which qualified for selection on one criterion but not on another. Had time been ample for complete analytical work on all soils this process of selection would have been gladly avoided. Eventually the following soils were chosen:

I	3.	1 horizon
IV	3.	2 horizons
VII	2.	3 horizons
IX	2.	4 horizons
LW	1.	5 horizons
UW	2.	6 horizons
M	1.	6 horizons
Ok	2.	5 horizons

giving 32 "selected soils".

III 4.3

Presentation of Results

In the following Tables, all results have been converted to an oven-dry (OD) basis, and in many cases considerably "rounded-off". Dashes in the Tables usually indicate that no analysis was possible because no sample existed (for example; M 1.1 in Table 16B), or they may fill a space to indicate that no meaningful figure can be placed there (for example; in Table 16B there can be no Total for Profile %Mg). "n.d." means "not determined".

Complete results appear in the tabular matter, but graphs are often simplified for clarity by taking means of two profiles on any particular surface.

IV

RESULTS

IV 1. INTRODUCTION

The analytical results reported in this section are divided for convenience into five loosely-named but logical groups:

- IV 2. "Physical" parameters. (Depths of horizons, reaction, loss-on-ignition, weights of L, FH and roots, weights of organic matter, gross soil separates, bulk density, and mechanical analysis.)
- IV 3. "Organic" parameters. (Oxidisable carbon, nitrogen, C/N ratios, cation exchange analyses, and multiple regression relationships between cation exchange capacity, oxidisable carbon and clay.)
- IV 4. "Total" analyses. (Total calcium, magnesium and potassium, total sulphur, and Tamm acid-oxalate extracts of soils and clays.)
- IV 5. Phosphorus analyses. (Total and organic phosphorus, inorganic phosphorus fractions, phosphate sorption.)
- IV 6. Mineralogical analyses. (X-Ray diffraction analyses, optical mineralogy by Dr K.R. Gill.)

At this point it is a pleasure to record my debt of gratitude to Mr J.S. Armstrong, Department of Forestry, Australian National University, for considerable help in the computation of regression analyses. A Control Data 3600 computer provided additional multiple regression data, and all the linear regressions reported hereafter. A "curvature" term incorporated in the simple linear regression program indicated non-linearity of many relationships.

IV 2. "PHYSICAL" PARAMETERS

Trends in soil reaction are shown in Table 10A. There is a general pH decrease with age, and with very few exceptions pH increases down each profile regardless of age. Upper horizons become acid earlier than lower horizons, with some very low values (3.5 in M 1.FH) in FH and .1 horizons of older soils. Soil reaction trends have not been graphed.

Table 10A also presents Loss-on-ignition (LOI) data. As expected, these values are very high in horizons of organic matter (OM) accumulation. Weights of OM have been calculated (Table 10B) from the LOI data on the reasonable assumption for these soils that $LOI = OM$. There is a general increase of OM with age, with a slight decrease after Mapourika, at an approximate rate from VII to M of $4 \text{ kg/m}^2/\text{millenium}$, or $4 \text{ g/m}^2/\text{ann}$. Quite large amounts of OM are held in the L and FH horizons of the older soils. As expected, a graph of OM accumulation (not shown here) is similar in form to Fig. 14 - the accumulation of oxidisable C (oxid.C). The mean relationship between LOI and oxid.C, calculated from 30 pairs of results for L and FH samples (results not shown here) gave $\text{oxid.C} = 47\%$ of LOI, or organic C (org.C) = 61% of LOI, using a conversion factor from oxid. to org.C of $100/77$. The latter equation approximates to a conversion factor from org.C to OM of 1.6; not unlike a commonly accepted figure of 1.74. Depth functions of OM accumulation (seen in Table 10B) illustrate marked changes in differentiation of OM between horizons, especially in the three oldest profiles. After an initial moderately high level of OM in .1 horizons, UW 2.3, M 1.2 and Ok 2.3 exhibit very low weights of OM, followed by

considerable increases in the lower horizons. As there are very low weights and proportions of macro-roots in these horizons (Table 10A), few micro-roots (<2mm) will have been present, and thus the OM must have been illuviated from upper horizons in finely dispersed form. The percentages of roots show marked concentration in upper horizons; for instance, in Ok 2.2.

Table 11A presents gross soil separate data, showing a general tendency for the weight ($\text{kg/m}^2/75\text{cm depth}$) of soil in a tessera to decline. Weights of Fines and Whole Soil (in $\text{g/cm}^2/\text{cm depth}$) (calculated from Table 11A) are presented in Table 11B. There is a general tendency for the Whole Soil unit weight to decrease with age, while unit weight of Fines increases consistently. The depth functions of Fines (seen in Table 11B) are hard to interpret, but M 1. and Ok 2. clearly show very low values in upper horizons, considerable increases in M 1.3 and Ok 2.2, and a slight decrease in M 1.4, Ok 2.3, and subsequent horizons of the Mapourika profile. The very high values in Ok 2.4 and 2.5 are probably due to the completion of weathering of stones, to form a compact mass very evident in the profile morphology. These trends seem to be initiated as early as UW 2. Trends in Table 11A are best shown in Fig. 9. After initial irregularities there is a steady linear increase in the proportion of Fines, to 86% of the weight of soil in the tessera. Graph lines for coarse gravel and fine gravel lie sub-parallel with the Fines, possibly indicating a constant rate of weathering. Fig. 9 also shows the abnormally high proportions of Fines in X, which are reflected in a high unit weight of Fines in X (Table 11B), and in the profile as noticeably compact, rather poorly drained, gleyed horizons. Depth

functions can be inferred from Table 11A; the amounts of stones and coarse gravel in upper horizons approach zero in quite youthful soils, and M and Ok are practically devoid of these fractions in .1, .2 and .3 horizons.

Results of mechanical analyses of Fines are presented in Table 12, whose format is similar to Table 11A. The main trends are better explained with reference to Fig. 10, which also bears some resemblance to Fig. 9. Very little clay is formed with age - the maximum value achieved is 11.20% (non-OM-free basis) in Ok 2.4. Weathering of coarse sand to fine sand, and subsequently to finer particle sizes, is shown by the great disparity between youngest and oldest soils. Thus, not only does the weight of Fines increase with age (from 9% to 86% of the weight of the tessera between I 3.1 and Ok), but these Fines themselves are weathered to reduce the proportions of coarse sand from 85.1% (I 3.1) to about 15% (Ok), with concomitant large increases of fine sand and silt, and small increases of clay. Again the anomolous nature of X is seen in Fig. 10: its compaction, firm consistence and poor drainage can clearly be attributed to higher-than-normal proportions of fine sand and silt. From LW onwards, weathering appears to have been constant in intensity, judging by the sub-parallel graph-lines in Fig. 10. Fig. 11 demonstrates once again an orderly weathering of fines with age, excepting X. Unfortunately, there are insufficient other points around the 200 μ diameter point to show a sigmoid curve. Very considerable loss of coarse sand with age has occurred, and less than half of the gain in fine sand has been converted to silt. Lastly, depth functions of per cent clay accumulation (OM-free basis) (Fig. 12) show

spectacular changes. Very early in the sequence (VII, IX) clay accumulates in upper horizons, and this process is accentuated in LW and UW, which show substantially unchanged clay contents below a depth of about 40cm. Some evidence for clay illuviation may be present in the depth functions for M 1., and is clearly seen in Ok 2. However, there is insufficient evidence to differentiate between clay formed in situ and that illuviated from higher in the profile. The matter will be mentioned again in the Discussion.

IV 3. "ORGANIC" PARAMETERS

Analytical data illustrating the accumulation of oxid.C and N are tabulated in Table 13, and graphed in Figs. 13, 14, 15 and 16. Data for I 3.1 and IV 3. have been recalculated (footnote:Table 13) to allow comparison with older profiles 75cm deep, but Fig. 13 shows data extracted from the earlier study (see II 5. in this thesis for details). This is reproduced here to indicate (i) the mean rates of accumulation over 55 years of both oxid.C (converted from org.C) and N (oxid.C at 30.8 and 16.4 g/m²/ann. for mineral soil + FH and mineral soil only respectively, N at 2.23 and 1.36 g/m²/ann. for mineral soil + FH and mineral soil only respectively); (ii) the widening C/N ratio, which exceeds 10 in mineral soil + FH between 12 and 25 years of age, and in mineral soils only between 25 and 45 years of age; (iii) the considerable proportions of oxid.C and N held in the FH layer; and (iv) the lack of any apparent steady-state in either accumulation curve. It was mentioned earlier that if the Chronosequence were to be extended to soils older than 55 years of age, one of the points of interest would be the fate of the oxid.C and, especially, the N, in view of the impending disappearance from the botanical succession of any macro-N-fixing plants. These trends are shown in Fig. 14. Disregarding for the moment the collection of points near the origin, it is clear that amounts of oxid.C and N in the tesseras have continued to rise, at overall approximate rates of 1.5 g/m²/ann. and 0.044 g/m²/ann. respectively, in the 11,900 years between VII and M. Table 13 and Fig. 14 show continually widening C/N ratios. L layers exhibit values as large as 77.4 (in

Ok 1.L) and C/N ratios of FH layers are as high as 20.9 in IX and rise steadily to a maximum of 45.9 in Ok 1.FH. C/N ratios of the whole profile and of mineral soil only also increase steadily and reach their zenith in M 1., with slight, and larger, decreases in Ok 1. and Ok 2. respectively. These declines are probably due to better drainage within the slightly-sloping Ok profiles, with respect to the level, water-logged Mapourika profiles. The amounts of oxid.C and N held in the litter layers increase greatly by Mapourika, but the proportions held there are variable but tend to decline with age (Table 13). There does not seem to be any apparent steady-state in the accumulation of oxid.C, but the rate of increase of N (whole profile) is very low between LW and UW.

To resolve the confusion of points near the origin in Fig. 14, the accumulation of oxid.C and N during the first millenium has been plotted in Figs. 15 and 16. Despite poor duplication between pits in three cases, several trends are clear from both graphs. There is a period of very rapid accretion of oxid.C and N (whole profile) during the first 100 years, and after 500 years accumulation rates decrease considerably. This may represent an interim apparent steady-state. Amounts of oxid.C and N in the mineral soil increase at a steadily decreasing rate. Both graphs show an absolute decrease in whole-profile oxid.C and N content at 250 years - Stage IX. If this effect is real, it is tempting to ascribe it to a period of intense biomass accumulation, during which the low scrub association of VII changes to the dense, tall, rata-kamahi association on Stage X. Unfortunately, no quantitative data are available to illustrate this period of rapid change in the forest

ecosystem. Such a period of growth would require considerable amounts of N, much of which would be drawn from the L and FH layers. The apparent decrease in oxid.C content in the litter layers of IX, with respect to VII, may be due to a reduced annual litterfall during this growth-period.

Cation exchange (C.E.C.) analyses are first set out in Table 14A, with footnotes to explain some unusual features in the younger soils, which are probably due to a rapidly declining CaCO_3 content. Trends in percent base saturation (%BS) show consistent decreases, at first in surface horizons (VII 2.), and then in intermediate and lower horizons (IX 2.). Depth functions for LW, UW, M and Ok are substantially the same, showing about 15-25 %BS in upper horizons, and low to very low %BS in lower horizons. These depth functions, contrary to what might be indicated by soil reaction changes (Table 10A), are probably due to slow release of ions from weathering rocks, at a rate insufficient to saturate the increasing C.E.C. The higher general %BS of Ok compared to M is due to declining C.E.C. rather than to increasing T.E.B. (Fig. 17). The raw data in Table 14A are recalculated in Table 14B, and the trends illustrated in Figs. 17 and 18. The former graph clearly shows a rapid increase in C.E.C. to about 20 eq./m^2 in IX and then a linear increase at a slower rate to Mapourika, with a subsequent decrease. The curve has some similarities in form to that of oxid.C accumulation; and later in this section multiple regressions showing a close dependence of C.E.C. upon oxid.C are discussed. After a rapid decline from $33.71 \text{ eq./m}^2/75\text{cm}$ depth (I) to only $3.71 \text{ eq./m}^2/33\text{cm}$ depth (IV 3.) and a subsequent increase in VII, T.E.B. increases steadily and only slightly in all

soils older than X. This may also be evidence for a slow and constant rate of weathering of parent material, although Fig. 18 does not seem to support this contention. The peak in Ca^{++} at VII is an artefact due to the assumptions outlined in the footnotes to Table 14A. Ca^{++} is clearly the dominant exchangeable cation (in most cases at least twice the next most abundant cation), and K^+ almost always exceeds the abundance of Mg^{++} due to the highly micaceous parent materials of these soils. The peaks shown by all three curves at Mapourika are largely due to the considerable amounts of Ca^{++} , Mg^{++} and K^+ in litter layers of this soil. This, in turn, may be due to the presence of much highly-weathered rock in this soil, which subsequently becomes a less important source of readily available cations. Despite the proximity of Ok to the sea, Na^+ (m.eq.%) contents do not seem to differ unduly from other soils in the sequence. Some linear regressions between exchangeable and total Ca, Mg and K will be discussed in the next section (IV 4.).

The possible importance of oxid.C content in determining C.E.C. was mentioned above. Yuan et al. (1967) recently examined relationships between C.E.C., OM and clay by multiple regression analysis of data from various groups of Florida soils. Their format is followed fairly closely below, although their results are not directly comparable as they used OM rather than oxid.C as an input to their equations. In the present work, 69 mineral soils (no L or FH horizons were included) were combined into different groups of young and old soils, and upper and lower horizons.** Subsequently, the 32 Selected

** UW, M and Ok were old soils. Horizons regarded as morphogenetically eluvial were called upper horizons.

Soils were likewise divided. Table 15A lists the soil groups and relevant data. Table 15B shows simple correlation coefficients between the three variables. All correlations between %oxid.C and C.E.C. were highly significant at the 1% level, but highly significant correlations between %cl and C.E.C. were achieved only in All Soils, young soils, upper horizons of young soils, and in the young soils among the 32 Selected Soils. In each of these cases the correlation coefficient was much lower than the coefficient between %oxid.C and C.E.C. There were non-significant negative correlations between %cl and C.E.C. in upper and lower horizons of the old soils. Low but highly significant correlations between %cl and %oxid.C were achieved in All Soils and young soils, but this is probably fortuitous as both %cl and %oxid.C increase independently throughout the early part of the sequence. The multiple regression equations are listed in Table 15C, with the same format as the previous two tables. The R^2 values show that these equations are, with one exception, highly significant at the 1% level. The partial regression coefficient t tests gave very highly significant values for all except one b_1 (%oxid.C) coefficient, and non-significant values for nearly all b_2 (%cl) coefficients. Taken altogether, the R^2 and t test coefficients indicate that C.E.C. of these groups of soils may be predicted from their multiple regression equations; %oxid.C being the overwhelmingly important factor in determining C.E.C. The equations show that each percentile of oxid.C contributed from 1.68 to 6.29 m.eq. C.E.C., although the mean of 13 out of 14 b_1 coefficients was 2.44. The exception (lower horizons of young soils) may be an artefact related to the possession by this group of soils of the lowest mean C.E.C.,

mean %oxid.C and mean %cl (Table 15A) of any group. The b_2 coefficients for %cl ranged from 0.05 to 0.43, with a mean of 0.19. The largest b_2 coefficients are in young soils, and upper horizons of young soils. The above mean value strongly indicates clays dominated by illite. Lastly, the relative contributions of oxid.C and clay to C.E.C. may be calculated using data from Tables 15A and 15C. Table 15D confirms the highly important role of oxid.C in fixing C.E.C. In seven groups the contribution of oxid.C falls between 87% and 100%, in two others (young soils, and upper horizons of young soils) it is 76% and 80% respectively, and in the remaining five groups it exceeds 100%, indicating a negative contribution by clay to C.E.C. This curious paradox is seen, in the four most extreme cases, only in old soils. This may be due solely to a fortuitous decline in C.E.C. and simultaneous increase in %cl in old soils (see Figs. 17 and 10), or it may possibly be due to the formation of clay-organic matter complexes. Yuan et al. (1967) stated

"...The mathematical assumptions of this equation require a linear response of C.E.C. to both the clay and organic matter variables and no interaction between the two."

It is reasonable to suggest that interaction may exist in the old soils if such clay-OM complexes have been formed. Dr J.K. Syers (pers. comm.; letter, 15 January 1968) reported extremely resistant OM in the clay fraction of some of these soils; after three weeks of continuous peroxidation OM could still be obtained following HF treatment.

IV 4. "TOTAL" ANALYSES

Total phosphorus, calcium, magnesium and potassium were determined in sodium carbonate fusion extracts, and efforts were made to determine total iron and aluminium in the same extracts. Mention has been made (III 4.lviii) of difficulties encountered in these analyses. With iron, erratic and unpredictable differences as large as 500% between duplicate fusions sometimes occurred, despite perfect duplication between these same extracts in P, Ca, Mg and K analyses. While methodological difficulties precluded accurate Al analyses, the conclusion is inescapable that poor Fe results were due to some inherent variability between duplicate samples from some soils. Appendix III reports mineralogical analyses of some soils containing variable amounts of heavy minerals within a range of particle size fractions in coarse sand. Despite hand-grinding to sizes smaller than 100 mesh, it seems that it was not possible to prepare samples homogenous with respect to iron content. Section III 3.3 detailed the bulking procedures for the production of Composite samples from stones, coarse gravel and fine gravel. This procedure was tested for three soils (Table 18), with variable but poor results. For Ca, only the M 1.4 Composite-TOTAL pair are similar; for Mg the UW 2.4 pair show reasonable agreement; for K the UW 2.4 and Ok 2.4 pairs are moderately satisfactory; and for P only one pair (M 1.4) shows adequate agreement. Against the background of these checks the results in Tables 16B and 17 must be accepted with some caution.

Tables 16A and 16B detail Ca, Mg and K analyses on Fines and Composite samples. Totals for Profiles are

summarised, and additional information derived, in Table 17. The main trends with time are better seen in Fig. 19. Depth functions, especially of percentage values (Tables 16A, 16B), indicate initial rapid losses of Ca from Fines and even from Composite samples in all horizons, and subsequent steady declines in the percentage of all three elements. The lowest values are seen in surface horizons, while values for lower horizons more closely resemble those of the PM. Table 18 shows that even (apparently intact) stones do not retain their Ca, Mg, K and P against weathering under a warm, superhumid climate. The average percentage loss of K between I 3.1 and Ok 2.1 (2.08% in some 22,000 years) is approximately 0.1%/1000 years; identical with the average rate of weathering of K_2O from the 2-0.2 μ fraction of surface soils derived by Hensel and White (1960). Simple linear regressions between exchangeable and total Ca, Mg and K in Fines indicated non-significant and very low correlations between exchangeable and total Ca, and Mg, when both individual horizons, and Totals for Profiles, were compared. In addition, the curvature factor showed that a linear relationship did not exist. The relationship between exchangeable and total K was linear and significant:

Individual horizons

$$\begin{aligned} \text{compared:} \quad \text{Exch. } K^+ &= 1.13 + 0.0014(\text{total K}) \\ R^2 &= 0.747^{**} \end{aligned}$$

Totals for Profiles

$$\begin{aligned} \text{compared:} \quad \text{Exch. } K^+ &= -0.32 + 0.0023(\text{total K}) \\ R^2 &= 0.724^{**} \end{aligned}$$

Amounts of Ca, Mg and K in Fines and Composite samples (Table 17) show consistent trends, some of which are plotted in Fig. 19. The proportions of each element held in the Composite samples gradually decline as the coarser fractions of the soil weather to form Fines. Amounts of Ca and Mg decrease rapidly early in the sequence (Fig. 19) and then slowly and steadily decline, whereas K decreases in an almost asymptotic fashion with age. The amount of any element present in Fines is the result of the balance between loss to the vegetation and leaching processes, and gain from weathering of coarser fractions; but the curves in Fig. 19 represent total tessera element contents. These are the resultant of original PM content minus loss to leaching and vegetation, in the absence of significant additions from dust or rain. The shape of Ca and Mg curves can probably be interpreted as (i) an initial very rapid loss by leaching of calcite (and perhaps dolomite) during the first half-century; aided by (ii) rapid incorporation of these elements within growing vegetation; and (iii) slow steady loss by leaching of Ca and Mg weathered from moderately resistant minerals, during the period from 500 to 22,000 years. The loss of K may occur as follows: (i) rapid initial loss by leaching of K on mineral surfaces exposed by comminution of the PM; together with (ii) incorporation of K into the biomass; (iii) quite rapid loss by leaching of K weathered from interlayer positions within biotite during the period 1,000-12,000 years; and (iv) an apparent steady-state between 12,000 and 22,000 years, during which no K appears to be lost from the tessera, or perhaps in which slight extra-ecosystem gains balance slight leaching losses of K weathered from resistant minerals. The

"percentage remaining" data in Table 17 would appear to support these interpretations. Simple regressions of the data in Table 17 and Fig. 19 give satisfactory linearity for only Mg and K: (T = time in years)

<u>Total amounts</u> (kg/m ²)	Mg = 6.90 - 0.0002(T)	R ² = -0.964**
	K = 24.78 - 0.0009(T)	R ² = -0.885*
<u>Percentage remaining</u>	%Mg = 41.29 - 0.0009(T)	R ² = -0.964**
	%K = 58.94 - 0.0021(T)	R ² = -0.892*

Overall, K is lost 4.5 times faster (0.9 g/m²/ann.) than Mg (0.2 g/m²/ann.) on an "absolute weight" basis, and 2.3 times faster on a "percentage remaining" basis.

Total sulphur (S_T) in the 32 Selected Soils was determined by Mr J.A. Adams at Lincoln College, to whom I am grateful for permission to quote and discuss the results in Table 16C. The high concentration of S_T in I is probably mostly present as sulphide, detectable as H₂S during HCl treatment. Pyrites (FeS₂) is stable to HCl, so at least some of the sulphides in the PM must be in forms other than pyrites. The main trends are clear. Large amounts of sulphides in the PM are rapidly oxidised to give low concentrations of S_T in the lower horizons of VII, IX, LW and UW, with a concomitant accumulation in upper horizons, presumably organic-bound. N/S_T ratios for the whole profile appear relatively constant between 5.1 and 7.8 in all soils except I and IV. Lastly, gleyed horizons in older soils (M 1.3-1.6 and Ok 2.5) have high levels of S_T, again presumably as sulphide. Water-logged horizons of these soils emit sulphurous odours when disturbed.

Changes in "active" iron and aluminium determined in Tamm acid-oxalate extracts (Table 19A) are best traced in

Fig. 20. Fig. 20 appears to show (i) "active" Fe accumulates earlier and faster than "active" Al; (ii) the accumulation of "active" Fe, but not "active" Al, is depressed in a young, gleyed soil (X 1.); (iii) both "active" Fe, and Al, accumulate at the same rate between soils 1,000 and 5,000 years of age; (iv) "active" Fe achieves an apparent steady-state for the subsequent 17,000 years, as, no doubt, "active" Al would have done were it not for a considerable accumulation in Mapourika - an old, gleyed profile. Further details of these trends are seen in the depth functions of percent "active" Fe and Al (seen in Table 19A). Progressive surface enrichment of "active" Fe in VII 2. and IX 2. is not evident in the almost vertical depth-profile of X 1., but continues in LW 1. Perhaps the first hints of Fe eluviation may be seen in IX 2. and LW 1., and the trend is clearly established in UW 2., which is a strongly podzolised profile. The zone of maximum accumulation of percent "active" Fe moves steadily downward in the profile throughout the sequence VII - IX - LW - UW - M - Ok. While "active" Fe is highly concentrated in M 1.4 (a gleyed horizon), it is not concentrated in other gleyed horizons such as UW 2.2, M 1.5, M 1.6, Ok 2.3 and Ok 2.5. Percent "active" Al appears to behave in a different manner. No very prominent depth gradients appear in any soils younger than 5,000 years of age, and "active" Al has certainly not suffered eluviation-illuviation in company with "active" Fe. Gleyed horizons (X 1.3-1.6, UW 2.2) in the younger soils do not exhibit accumulations of "active" Al, compared with spectacular accumulations in gleyed horizons in the older soils (M 1.4-1.6, Ok 2.5). Relationships between "active" Fe and Al and (i) phosphate

sorption, and (ii) the "iron and aluminium-bound" inorganic phosphorus fractions, have been explored by linear regressions, which will be discussed shortly (IV 5.). It is unfortunate that total Fe and Al data cannot be compared with "active" Fe and Al.

Few clear trends are evident in the relationships between "active" Fe and Al in eight soils and the clays extracted from them (Table 19B). The ratio of weights of both elements in soils to the weights in clays increases with age in topsoils and also lower horizons, except in Ok 1.4. Evidently the "active" Fe and Al accumulate in the soil faster than in the slowly-increasing clay content. In fact, less "active" Fe and Al, on a percentage basis, are held in clays as the soils age, as the ratios $\text{clay}(\%)/\text{soil}(\%)$ decrease in both upper and lower horizons. The ratio of $\%Fe/\%Al$ falls consistently in topsoil and subsoil clays and soils, which confirms that "active" Fe accumulates rapidly in young soils whereas the rate of formation of "active" Al is rather slower. Lastly, the data are inadequate to derive clay silica/sesquioxide ratios, as an aid to interpretation of podzolisation or gleying.

IV 5. PHOSPHORUS ANALYSES

Many of the results of phosphorus determinations are presented in Table 20. Marked declines with age of P_T and P_t (p.p.m.) are evident, giving some indication of leaching rates in these soils. Weights of Total P determined by the ignition and fusion (P_t and P_T) methods are frequently similar for soils which are only moderately weathered and leached, and in fact this is nearly so for all the younger soils, including UW. M and Ok show much lower P_t than P_T , due to the inability of the ignition method to determine P occluded within developing concretions. The comparison is not invalidated by the small amounts of P in L, included in the P_T column. Except for I, IV and IX, which have moderately high concentrations of P_T but low volume-weights of Fines (and hence low weights of P_T), the almost linear decline in mean P_T from VII (about 265 g/m^2) to Ok (about 60 g/m^2) is interrupted only by X, previously shown to possess volume-weights of Fines abnormally high for this sequence of soils. Weights of organic P (P_o) increase rapidly during the first 1000 years, excepting the youthful gleyed X, and then reach an apparent steady-state for many millenia. These trends are clear in Fig. 21, which shows P_T and P_o in the Selected Soils only. Depth functions of percent P_o in horizons of the Selected Soils (Fig. 22) show with clarity low proportions and uniform depth-gradients in I 3.1 and IV 3., changing within a very few years to strong surface accumulation (VII 2., IX 2.) and subsequently steadily increasing accumulation in lower horizons. % P_o in upper horizons reaches about 70% very early in the sequence, and thereafter does not rise much above 85%. In 10,000 years, from M 1. to Ok 2., the depth gradient again becomes uniform and above 80%.

It was assumed that all P in the Composite samples was inorganic, which may only obtain in samples from the younger soils in the sequence. Absolute amounts of P_T in Composite samples (Table 20, and summarised in Table 21) decline markedly, and the percentage in these samples (Table 21) with respect to the percentage of P_T held in Fines also declines. A footnote at the end of Table 20 shows concentrations of P_T in three "grab-samples" collected 1, 2 and 3 metres below an Okarito profile similar to Ok 2. The data indicate a further depth-gradient of p.p.m. P_T , rising to a value not much smaller than in PM. Fig. 23 depicts the information in Table 21. P_T within the I and VII Composite samples seems unduly high; a point which may also be observed for I, but not VII, in Table 17 and Fig. 19. The volume-weight of fractions coarser than Fines may possibly be abnormally high in I 3.1. Absolute amounts of P_T in Fines do not decline nearly so fast as amounts of P_T held within the coarser fractions, probably because loss of P from Fines is resisted by the formation of organic, and non-occluded and occluded inorganic, P. Also, P_T in Fines is continually supplemented by P from weathering Composite samples. Simple regressions against time (T in years) of data in Table 21 showed non-linear curves for loss of Fines P_T and Composite P_T , but linearity of the regression (Fines+Composite) P_T (now called TOTAL P_T) on time was satisfactory with the correlation coefficient significant at the 5% level:

$$\text{TOTAL } P_T = 978.1 - 0.0487(T) \quad R^2 = -0.807^*$$

The proportions held in Fines and Composite samples gave complementary linear regressions on time, significant at the 1% level:

$$\begin{aligned} \%P_T \text{ in Fines} &= 23.9 + 0.0029(T) & R^2 &= 0.893^{**} \\ \%P_T \text{ in Composite} &= 76.1 - 0.0029(T) & R^2 &= -0.893^{**} \end{aligned}$$

To remove the effects of I and VII on TOTAL P_T , the regressions were repeated with data from LW, UW, M and Ok only. Linearity was now satisfactory, but the low number of degrees of freedom inherent in only four variables produced non-significant (at the 5% level), though high, correlation coefficients. As the period from LW (1,000 years of age) to Ok (22,000 years of age) represents a phase of steady P loss in a sequence of ecosystems probably of relatively constant biomass, the regressions are a good indication of loss-rates by leaching.

$$\begin{aligned} P_T \text{ in Fines} &= 240.3 - 0.0075(T) & R^2 &= -0.900 \\ P_T \text{ in Composite} &= 430.2 - 0.0223(T) & R^2 &= -0.835 \\ \text{TOTAL } P_T &= 670.5 - 0.0298(T) & R^2 &= -0.937 \end{aligned}$$

$\%P_T$ in Fines and Composite samples again gave complementary linear regressions:

$$\begin{aligned} \%P_T \text{ in Fines} &= 35.8 + 0.0022(T) & R^2 &= 0.870 \\ \%P_T \text{ in Composite} &= 64.2 - 0.0022(T) & R^2 &= -0.870 \end{aligned}$$

Some of these figures will be discussed later in this thesis.

Inorganic P in the 32 Selected Soils was fractionated into seven forms (Williams et al., 1967), which in this thesis will be grouped thus:

Easily-sol P)	
NH ₄ F-P)	non-occluded inorganic P
1st NaOH-P)	
Red-sol P)	
2nd NaOH-P)	occluded inorganic P
HCl-P)	acid-extractable Ca-P
Residual inorg. P)	residual inorganic P

Concentrations of P in the individual fractions are shown in Table 22A. P_T minus P_O should equal the sum of inorganic P fractions (ΣP_i); agreement is reasonable except in some upper horizons of UW and M, and throughout the Ok profile. Possible error in the sum of seven fractions is large even if analytical errors for each fraction were very low, but the discrepancy evident in Ok is probably mostly due to the errors inherent in the ignition method for determining P_O . P_T (Table 20) and ΣP_i (Table 22A) may be taken as accurate within reasonable analytical error, so $P_T - P_O$ figures (Table 22A) consistently lower in Ok (especially in surface horizons) must be due to overestimation of P_O by the ignition method. In this method, $P_O = P_t - P_a$ (where P_a is the inorganic P in a non-ignited sample). Ignition of horizons high in occluded inorganic P (see Ok 2.1 and 2.2 in Table 22C) probably increases solubility of P in $N H_2SO_4$, and thus P_O is greatly overestimated. Syers (1966) and Williams and Walker (1967) have discussed aspects of this problem. Changes between and within soils of groups of inorganic P fractions (p.p.m.) are best examined in the depth functions (which can be read from Table 22A). With time, non-occluded inorganic P increases markedly in upper horizons (VII 2., IX 2., LW 1.) for 1,000 years. During the following 21,000 years values in surface horizons fall to about 50 p.p.m. while non-occluded inorganic P accumulates spectacularly in lower horizons of UW 2. and M 1., only to decline to very low levels in Ok 2. Likewise, occluded inorganic P first accumulates in surface horizons (VII 2., IX 2., LW 1.), but UW 2. has large concentrations in lower horizons, which are not gleyed. Some gleyed horizons in UW 2., M 1. and Ok 2.

exhibit low levels of occluded inorganic P. High levels in Ok 2.1 and 2.2 are probably due to development of iron concretions with age. Concentrations of acid-extractable Ca-P decline markedly, especially in surface horizons (IX 2.), and the trend continues consistently until Ok 2., which has no acid-extractable Ca-P. The fate of this fraction will be discussed shortly. Concentrations of residual inorganic P are unlike the previous depth functions. This fraction always contains between 15 and 24 p.p.m. in all horizons in all soils. Variations with depth lie within analytical error and cannot be ascribed to the effects of any soil forming processes.

Some points mentioned by Williams et al. (1967) require discussion, with reference to the present investigation:

(i) Williams found very large amounts of easily-soluble P were removed by repeated extraction of Stage IV and VI FH horizons. The present author did not repeat this work on other FH horizons, but highly-organic horizons (UW 2.1, M 1.1, M 1.2, Ok 2.1) contained amounts of easily-sol P many times greater than all other horizons.

(ii) CaCO_3 in I 3.1 sorbed P from the $\text{NH}_4\text{F}+\text{P}$ extractant. This P was not recovered in any following extractant until recovered in 1st HCl-P.

(iii) The ratio of P determined in 2nd HCl-P to that in 1st HCl-P was low where HCl-P was high, and where it formed a large proportion of ΣP_i , as shown in Fig. 1 in Williams et al. (1967). About 10 p.p.m. P was found in most 2nd HCl-P extracts.

(iv) Amounts of residual organic P (results not shown in this thesis) appeared to be closely correlated with amounts of organic P.

Weights of the various inorganic P fractions have been tabulated (Table 22B) and plotted (Fig. 24). Amounts of acid-extractable Ca-P at first follow the curve for ΣP_i (which bears close resemblance in form to P_T in Fig. 21), but then decline rapidly to zero by 22,000 years. As this fraction is lost, most of it is converted to organic P (not shown on graph), and to non-occluded and occluded inorganic P fractions, during the first 1000, and possibly 5000, years. During the next 7000 years the decline in acid-extractable Ca-P parallels the decline in ΣP_i . This fraction may be converted to non-occluded inorganic P (which increases only slightly), and to occluded inorganic P (which decreases), and a portion of those fractions could be lost by leaching. During the following 10,000 years the remnant 19.5 g/m^2 of acid-extractable Ca-P is lost by conversion to other fractions and subsequent leaching, or by direct leaching: the increases between M and Ok of occluded (14.3 g/m^2) and residual (2.9 g/m^2) inorganic P do not balance the decreases of acid-extractable Ca-P and non-occluded inorganic P (60.8 g/m^2). Acid-extractable Ca-P may be converted to organic P and then lost; absolute amounts of this form decrease during this period. There is an apparent steady-state in weight of non-occluded inorganic P between UW and M. Low amounts of occluded inorganic P in M 1. are no doubt due to the heavily gleyed nature of this profile.

The proportions of ΣP_i held in the various inorganic P fractions are shown in Table 22C, and plotted in Fig. 25.

The decline of acid-extractable Ca-P at a decreasing rate is clearly shown, together with a concomitant linear rate of increase of non-occluded inorganic P for 12,000 years. During this time occluded inorganic P rises and then falls, while residual inorganic P gently increases. In the last 10,000 years the proportions of occluded and residual inorganic P rise to 48.6% and 28.7% respectively, while non-occluded inorganic P declines sharply. The trends are seen in more detail as depth functions (in Table 22C). Non-occluded inorganic P, starting from very low values, increases in upper horizons throughout VII 2., IX 2., LW 1., UW 2. and M 1., while an increase in lower horizons is first seen in UW 2.4, subsequently reaching high levels in the three lowest horizons of M 1. A very sharp change in depth gradient between M 1.2 and M 1.3 is notable. Likewise, occluded inorganic P first increases steadily in upper horizons, with the exception of M 1., and never reaches very high proportions in lower horizons, especially in M 1. Acid-extractable Ca-P declines rapidly in surface horizons and later in lower horizons. Lastly, the proportions of residual inorganic P show marked depth gradients only in the three oldest soils, but the concentrations of this fraction did not change (see Table 22A).

Some changes in amounts of organic, and forms of inorganic, P (Tables 20, 21) are shown in histograms in Fig. 26. P in the Composite samples has not been fractionated, but may occur largely as acid-extractable Ca-P, particularly in the early Stages. Gains, losses and transformations of P have been discussed at length above, so it is only necessary to summarise nett changes over 22,000 years into the following Table.

Nett Changes in Phosphorus over 22,000 Years
(g/m²/75cm profile; figures "rounded-off")

	<u>I 3.1</u>	<u>LW 1.</u>	<u>M 1.</u>	<u>Ok 2.</u>	<u>Nett Change (I-Ok)</u>
<u>P in Composite samples</u>	1177	558	59	18	-1159
<u>Acid-extractable Ca-P</u>	108	110	20	0	- 108
<u>Non-occluded inorganic P</u>	1	20	71	10	+ 9
<u>Occluded inorganic P</u>	3	7	7	22	+ 19
<u>Residual inorganic P</u>	3	4	10	13	+ 10
<u>Organic P</u>	2	53	54	32	+ 30
TOTALS	<u>1294</u>	<u>753</u>	<u>229</u>	<u>76</u>	<u>-1199</u>

A loss of 1199 g/m² of P represents 92.7% of the P in Stage I.

Weights of "active" Fe and Al have been regressed against weights of some inorganic P fractions. Linearity was unsatisfactory in the regression of NH₄F-P on "active" Al, but very high in two other regressions of 1st NaOH-P on "active" Fe, and the sum of 1st NaOH-P, red-sol P and 2nd NaOH-P on "active" Fe. All correlation coefficients were highly significant at the 1% level:

$$\begin{array}{llll}
 \text{NH}_4\text{F-P} & = 0.49 + 9.48(\text{"active" Al}) & R^2 & = 0.567^{**} \\
 \text{1st NaOH-P} & = 0.36 + 4.87(\text{"active" Fe}) & R^2 & = 0.620^{**} \\
 \text{sum of 3 fractions} & = 1.18 + 9.38(\text{"active" Fe}) & R^2 & = 0.698^{**}
 \end{array}$$

Table 22D shows percent P sorption from NH_4F extracts under the specialised conditions of the inorganic P fractionation scheme (see III 4.1xi). Figures obtained in this manner are not comparable with any obtained by more conventional methods of measuring P sorption from solution. The highest value achieved (90.6% in UW 2.3) was in an horizon composed solely of an iron pan 1cm thick, which also has the highest % "active" Fe. Percent sorption was regressed on both % "active" Fe and Al. The former regression was linear with a highly significant correlation coefficient:

$$\text{Percent sorption} = 5.61 + 91.53(\% \text{ "active" Fe})^2$$

$$R^2 = 0.803^{**}$$

whereas a regression on "active" Al was highly non-linear with a low, non-significant, negative correlation coefficient. In the presence of NH_4F , which dissolves aluminium-bound P, sorption must be accomplished by "active" Fe surfaces. Thus, the significance of sorption data obtained in this manner is doubtful, and such data certainly cannot be related to sorption by "active" Fe and Al under natural conditions, or compared with data obtained by more conventional methods.

IV 6. MINERALOGICAL ANALYSES

Through lack of time, the present author confined mineralogical work to X-Ray diffraction (XRD) studies of 16 samples from 6 soils (Table 23), but Dr K.R. Gill, Petrologist, New Zealand Geological Survey, examined coarse sands (ex mechanical analysis) of the same soils. His report, dated 31 March 1967, is reproduced in Appendix III. I am extremely grateful to Dr Gill for his work on these samples.

Since the samples subjected to XRD were not prepared quantitatively, the observed trends (Table 23) are based only on a rough "scoring system", and must be interpreted with caution. Furthermore, clay mineralogy may change rapidly with depth in podzol profiles. Thus, within-profile variations may mask between-profile changes due to soil formation over a period of time. As only a few topsoil horizons have been examined, the trends in Table 23 do not delineate the complete mineralogy of podzol pedogenesis.

Firstly, quartz increases with time from weak to very strong in sands, from very weak to very strong in silts, and only appears in clays in M 1.2 and Ok 2.2. Plagioclase feldspar is very weak to weak in sands and silts of I 3.1, VII 2.1 and IX 2.3, but increases to strong in UW 2.2, and first appears in clays in this soil. Thereafter it declines to negligible amounts in all three fractions of Ok 2.2. Declining mica contents seem to parallel increasing quartz contents; mica is lost from sands by UW 2.2, decreases to a trace in silts by M 1.2, and also decreases in clays from very strong to very weak throughout the sequence. As mica disappears,

hydrous mica increases steadily in clays first and then silts, but is never found in sands. Lastly, chlorite is present in all three fractions of VII 2.1 and IX 2.3, but speedily disappears from sand and clay in UW 2.2 and is absent in the two oldest soils.

The report by Dr Gill gives much more information than the XRD data, but some aspects are perplexing. After studying the report Mr J.D. Raeside, Senior Pedologist, New Zealand Soil Bureau, made the following points (inter alia) in a letter (dated 23 May, 1967) to Professor T.W. Walker.

1. Potash feldspar is not recorded for the youngest soils but is present in the three oldest soils. If the two oldest soils are sufficiently weathered for plagioclase, green hornblende, mica and epidote to have disappeared, potash feldspar should also have disappeared.

2. Hydrobiotite (oxidised rock fragments) survives in UW 2.2 and Ok 2.2, although it should have disappeared in the oldest soil. If loess contaminated Ok 2.2, mica, chlorite and other minerals should also be present.

3. Zircons were recorded only in the oldest soils.

4. The disappearance of mica, chlorite, feldspars, green hornblende and epidote may be adequately explained as a weathering sequence.

5. Biotite, hydrobiotite and potash feldspar in the oldest samples may have been derived from garnet oligoclase gneiss, forming the PM of the oldest, but not youngest, soils.

Some of the implications of this sparse mineralogical information will be discussed later, with reference to the constancy (or otherwise) of PM throughout the Chronosequence.

V

DISCUSSION

V 1: CONSTANCY OF SOIL FORMING FACTORS, OTHER THAN TIME

Early in the Review of Literature (II 1.1) it was stated:

"If the nature of the Time factor is to be investigated all the other soil forming factors must be kept constant or ineffectively varying."

Some mathematical expressions then illustrated theoretical effects of the "range" and "effectiveness" of any variations in the State Factors. This section will examine in some detail these aspects of the State Factors Climate, Organisms, Relief and Parent Material, and the effects of Man, in relation to the Franz Josef Chronosequence.

V 1.1

Climate

There are few data upon which to base inferences about past climates in the Franz Josef region. No published palynological data are available, and no reliable assertions about climatic effects are possible from the postulated Ice-age snowline depression (Willett, 1951). Climatic changes have influenced ecological successions (II 4.2) and these may have had some secondary effects on the soils (see below). In the absence of reliable information about even gross climatic changes, let alone such subtle climatic parameters as frost, fog and seasonal rainfall variation, it can only be assumed that a superhumid climate with considerable excess of precipitation over evapotranspiration has prevailed for the last twenty millenia.

"...of present-day soils, only those of Post-Wisconsinan age can be monogenetic, and even these have experienced at least minor climatic changes." (Thorp, 1965)

Stephens (1965) has warned that

"The integration of leaching is not necessarily continuous, for at times the rainfall may have been insufficient to leach and drain the profile."

While this condition would not have obtained in the Franz Josef region, the probability of a non-constant rate of leaching must be recognised. However, Fig. 19, for example, seems to indicate relatively constant rates of loss of Mg and Ca over the periods of 1-5, 5-12 and 12-22 thousand years ago.

Neither is the present-day climate over the region uniform. Rainfall increases eastward from the township

to the Glacier terminus (Stevens, 1963) and decreases westward to the coast (Westland National Park Handbook, 1965); the differential between Stages I-VII and Okarito may be as great as 100"/annum. Thus it cannot be claimed that Okarito soils now suffer the same leaching-potential as younger members of the sequence, although it is possible that more humid conditions during the Climatic Optimum may have minimised the present differences. In the short-term period encompassed by Stages I-VI, climatic variability, especially in rainfall, may have had differential effects on the soils, but these have probably been masked by variations in other State Factors, such as gross mechanical composition of the PM.

V 1.2

Organisms (Biotic Factor)

It is difficult to define and evaluate possible effects of an inconstant Biotic Factor. Crocker (1952) has discussed the complex dual nature of this State Factor: its dependence upon Climate and soil (expressed as the Effective Disseminule Factor), and the postulated independence of the Total Disseminule Factor, or available biota. It can only be assumed that the available biota was uniform in composition over the restricted area containing this Chronosequence, in which case all soils have by definition had a constant Biotic Factor. Jenny's concept of a Chronosequence must in theory consider all Soil Forming Factors independent of each other. In practice, migration of Westland podocarp communities after recent climatic change (described in II 4.) is evidence of a non-independent, and non-constant, Effective Disseminule Factor. The lowland terraces west of the Alpine Fault probably carried bog and swamp vegetation until the start of the last millenium. Change to dense podocarp-hardwood communities may have facilitated general increases in depths to the water-table, and the processes of gleying may subsequently have diminished in importance. However, the impress of a different community over such a short period may not have materially affected such soils, whose characteristics were developed under different conditions for many millenia.

To this author's knowledge, there is little evidence that populations of faunal macrobes* have differentially

* A useful term coined by G.V. Jacks to denote macroscopic fauna and/or flora.

affected particular soils in the sequence. Goats and pigs are not seen in the vicinity of these soils, and deer and chamois seem to avoid the wetter forests, although this author has observed slight grazing damage on open river flats such as Stage III. The effects of opossums, common in these forests, are hard to assess, although they are unlikely to have greatly affected the soils save by reducing litter-fall. Areas with any opossum excreta were avoided when selecting pit-sites. The soils show no bioturbic characteristics, and no significant additions of extra-terrestrial guano are likely. While surface dimpling of the soils by tree windthrow is common, such areas were also avoided during pit-site selection. Lastly, some differences between soils in the occurrence of earthworms were observed. The least acid topsoils, principally Stages IV, VII and IX, often contained two to four large worms per square metre, which seemed to obliterate the sharp boundary between FH and .1 horizons evident in Stages V and VI. These two Stages, isolated from the valley walls (and older soils) by barren alluvial terraces, did not contain earthworms. To this extent Stages V and VI have not enjoyed the same faunal Biotic Factor as IV, VII and older soils.

V 1.3

Relief

All soils were sampled on absolutely flat sites, with the important exception of the Okarito pits, which lie on five (Ok 1.) and ten (Ok 2.) degree slopes (see III 3.1). Stevens (1967) stated

"...the differences in slope may mean that the Okarito was not necessarily at one time a Mapourika, and interpretation of trends in soil formation must be cautious."

The profile descriptions in Appendix I indicate certain differences between Ok 1. and Ok 2.; principally in the depth of the blue-grey (5B 6/1) gleyed .3 horizons. Ok 1.3 is about 25cm (18-30cm) deep, with a few brownish-yellow mottles; Ok 2.3 is about 10cm (0-15cm) deep with many reddish-yellow mottles. These differences presage more runoff from Ok 2. than Ok 1., and hence less infiltration and leaching. Nevertheless, the former does not seem to be significantly less leached, judging from the assorted analytical data presented in the Tables. When compared with the Mapourika profile, differences are more apparent, as the younger soils on the flatter sites are gleyed in the lower horizons, have deeper and heavier FH horizons, and exhibit low proportions of occluded forms of inorganic P (Fig. 25). In conjunction with the lower rainfall near the coast, the Okarito soils would appear to have escaped the severe rates of leaching suffered by younger soils under higher rainfalls.

The depth at which the water-table is reached is largely controlled by relief, but may also be affected by internal conditions in the soil. Many combinations of these influences are seen in soils of the Franz Josef

region. All the younger soils in the Chronosequence are freely-drained; but in a young soil with fine textures and slightly cemented horizons (Stage X), and in older soils, much water is held in the profile as a perched water-table, and some gleying ensues. The PM of the Okarito soils appears to be an extremely compact basal till, overridden by the Glacier, overlain by a metre of looser ablation moraine in which the soil has developed. In some areas a series of highly-indurated iron pans has formed at the junction of the two tills, often producing gleying above the pans. A complex jumble of different kahikatea (Podocarpus dacrydioides) communities near the mouth of the Waiho River reflects a delicate balance between high and low water-tables imposed on the soil by macro- and micro-relief, by fine- and coarse-textured alluvia, and by the development of differential drainage capacities during soil formation due to mor layers, interlaced roots and iron pans.

V 1.4

Parent Material

The moraines and terraces on which the soils of the Chronosequence have been formed are all derived from the restricted geological and geographical range in and around the névé of the Franz Josef Glacier. In the letter reproduced in Appendix III Dr Gill stated

"...the mineralogy of your samples appears to be "normal" as far as the known source rocks are concerned and with no exotic species...the samples containing abundant rock fragments are typical of the metamorphic rocks of the Alpine belt..."

However, three inter-related possibilities must be considered: contamination by material from outside the region, inconstant mineral suites in soils of the sequence, and inconstant physical and chemical parameters of parent materials throughout the sequence.

There is no evidence of contamination by past additions of pyroclastic material, such as pumice from the South Sandwich Islands which reached the West Coast in 1964 (Coombs and Landis, 1966). C.O. Hutton (1950) found occasional deposits of the phosphate-bearing mineral monazite on some West Coast beaches, but it is doubtful whether these could contaminate inland moraines and terraces. Stevens (1968; in press) has discussed the possibility of loess on the Okarito soils, with reference to a recent paper by Young (1967). It was concluded that significant additions of loess are unlikely. In this respect, Okarito soils near Okarito differ from Okarito soils developed in deep loess on terraces and moraines in north Westland.

Some perplexing mineralogical evidence derived from a limited number of coarse sand samples has been mentioned in IV 6. The anomolous presence of hydrobiotite and potash feldspar, unaccompanied by mica, chlorite and others, in the oldest samples tends to confirm the absence of loess. It is difficult to see how hydrobiotite and potash feldspar alone could have remained in some positionally unweatherable site for twenty millenia, so it seems most likely that these minerals may have been derived from garnet oligoclase gneiss in the PM of the oldest, but not youngest, soils. Okarito soils could conceivably have been affected by Greenland series greywacke from McDonald's Creek or The Mummy (Gunn, 1956), or by granite from Canavan's Knob. The present author found one pebble of granite in a cutting on the Okarito road.

Some effects of differential compaction of PM have already been mentioned, with reference to Okarito soils. While recent flood deposits were scrupulously avoided during site-selection, soils with abnormally high contents of fine particles, such as Stages IV and X, were encountered. Such soils usually possess low porosities and high volume-weights of Fines, and may be gleyed. A noticeably contagious distribution of Coprosma rugosa on Stage IV was attributed to this effect. Varying proportions of greywacke, biotite schist and garnet oligoclase gneiss in alluvia could result in widely varying proportions of certain minerals, such as quartz, which undoubtedly could affect contents of phosphorus and other elements. The amount and distribution of various index minerals in these soils has not been determined, so methods of assessing soil development (Barshad, 1964) are

not applicable to this Chronosequence, even if the difficulties posed by Raeside (1959), and the stony nature of these soils, could have been overcome. An examination of the particle-size distribution of the non-clay fraction (Table 12) (as in Barshad, 1964; p.10) indicated examples of non-stratification (Stage X) and marked stratification (Stage IX, Lower Wombat), but the picture is confused by erratic occurrence of stones within profiles.

The evidence regarding PM constancy is thus incomplete, inconsistent and unhelpful. Plant ecology and soil morphology may be greatly affected by variations in relief and soil physical characteristics, but the possibility of subtle chemical differences between rocks and mineral assemblages in parent materials cannot be denied. In particular, the oldest soils may have been formed on parent materials rich in garnet oligoclase gneiss with respect to younger soils in the sequence. Parent materials of this gneiss could possess heterogeneous P contents.

V 1.5

Man

Bidwell and Hole (1965) discussed Man's impact on the soil, and some anthropic influences on the five Soil Forming Factors. The evidence relating to these influences in the Franz Josef region is scanty and inconclusive. McCaskill (1960) mentioned the presence of a large semi-permanent Maori pa at Okarito, but apparently these people ate marine and estuarine fauna and may not have disturbed inland birds. Any resulting soil disturbance is impossible to assess. The present author has not discovered any evidence near Okarito of "Maori-soils" similar to those in the Waikato described by Taylor (1958). Gold was mined for many years in the region, especially at Okarito, McDonald's Creek, and near the confluence of the Callery and Waiho Rivers (May, 1967; Westland National Park Handbook, 1965). Evidence of sluicing is obvious near the Franz Josef township, and such areas were rigorously avoided during site-selection. Silver pine cutters in the Okarito area may have had more serious effects on soils. According to local residents, a band 3 miles wide south of the Forks-Okarito road was creamed for silver pine (but no other species) near the end of the Nineteenth Century, and again some 50 years later. This light logging did not disturb the mineral soil at the Okarito pit-sites, but it undoubtedly altered litter-fall, opened the canopy, and may have affected water regimes by decreasing interception and infiltration, and increasing runoff. These effects have probably not influenced nutrient contents in these old and infertile soils, but L and FH layers are no doubt thinner under the logged stands than in the natural state. Pakihi areas on

either side of the Forks-Okarito road have been repeatedly burnt during the last century, but these fires did not extent into the region of the Okarito pit-sites.

Finally, it is apposite to mention some recent geographical changes in the region. During 1967, which recorded an abnormally high rainfall of about 280", floods swept away all of the Stage II surface. The Waitangitaona River changed course and now flows into Lake Wahapo and thence to the sea via the much-enlarged Okarito River. Stage IV was largely destroyed by earth-moving machinery in 1967, and the present writer has been told that parts of the Lower and Upper Wombat terraces have likewise been desecrated. Lastly, a road diversion has removed the ridge on which the Mapourika soil was situated.

V 2. THE METHOD OF INVESTIGATION

V 2.1

The Present Work

Apart from the matters of "theoretical" interest discussed above, some aspects of the methods of investigation are subject to error. These may be briefly enumerated:

1. In pits on the younger Stages some difficulty was experienced in compensating for the volumes and weights of boulders projecting into the pit. Smooth-faced profiles could easily be produced in pits on older surfaces.

2. Similarly, a few pits contained large knots of roots enclosing stones or mineral soil. Volume-weights of mineral soil in such pits could be underestimated by up to 15 kg/m²/profile.

3. Occasionally, weights of large boulders had to be estimated. The probable error is not likely to exceed $\pm 2\%$ of the volume-weight of stones in any given horizon.

4. The errors inherent in the bulking procedure for Composite samples have been mentioned (IV 4.).

5. Henzell et al. (1967) proposed a method for overcoming analytical errors due to "puffing-up" of mineral soils by organic matter. Their calculations would be inappropriate for this study because (a) the Franz Josef soils are far too stony, and (b) their samples are not necessarily collected solely from genetic horizons.

V 2.2

Possibilities for Future Research

Glaring deficiencies in the scope of the present work are obvious. There has been no attempt to sample the forest biomass; a rich field awaits the valiant soul prepared to tackle the difficulties outlined in the next section. Work on the seasonal dynamics (litter-fall, organic cycle, ecosystem balance sheets) of Westland podocarp forests is sorely needed. Thirdly, the absence in associations on older surfaces of higher plants known to fix atmospheric nitrogen poses the considerable question of sources of N after the elimination of Carmichaelia grandiflora.

Many problems of pedogenesis remain. Detailed studies of soil variation on particular surfaces would allow more confident assessments of pedogenetic change than are possible from duplicate pits. Intensive sampling, and much optical and clay mineralogical work, are necessary to establish PM constancy and elucidate weathering processes. The micro-morphology of the soils in the Franz Josef Chronosequence merits study. Lastly, an extensive investigation of silica and sesquioxides in a wide range of clay separates is necessary before the processes of gleying and podzolisation in these soils can be properly delineated.

V 3. ECOSYSTEM DYNAMICS

An early aim of this study was to characterise nutrient gains, losses and redistributions within the vegetation tessera as well as in the soil. In this manner an almost complete picture of ecosystem processes might have appeared.

The elucidation of organic production, turnover and mineral cycling in woodland ecosystems (for example, see Ovington, 1965) demands complete felling, weighing and dissection of large areas of forest (Greenland and Kowal, 1960); or of smaller areas (Ovington et al., 1967); or of individual trees (Miller, 1963a-c). While biomass determination in even-aged coniferous monocultures (reviewed inter alia by Ovington, 1962) is arduous and difficult enough, large resources of time, labour and facilities are necessary for similar studies in all-aged mixed forests containing up to six tree species and many understory species, in as many as five tiers. Any approach based on selection of an "average" tree is doomed to serious error (Madgwick, 1963). Even placement of litter trays requires extensive replication and several years (Ovington, 1965) of records before reliable estimates of current litter-fall are available.

The original aim was thus too ambitious, and a further plan was formulated. The National Forest Survey (N.F.S.) established plots in the Franz Josef region, and per acre wood volumes for many species are available. A density factor might have given wood weights, and use of appropriate analytical figures (from the Forest Research Institute, perhaps) might have provided approximate above-ground weights of a few nutrients. In practice, too many

assumptions are involved and results are meaningless. Firstly, N.F.S. plots are rarely located near the soil pits, and data from these plots are subject to considerable published coefficients of variation. Secondly, only volumes of boles of merchantable species were determined, omitting branches and leaves, and also non-merchantable species. Thirdly, analytical data for Westland podocarp and hardwood timbers did not seem to be available, and wood densities are notoriously variable and site-dependent.

For these and other reasons, such as difficulty of access and lack of labour, the present author reluctantly discarded thoughts of total ecosystem analysis. Vegetation within metre-square quadrats in Stage VI contained about a quarter and a half of the nitrogen and organic carbon respectively in the soil+vegetation ecosystem. It would have been of great interest to know the proportions of C, N and P held above ground in ecosystems on older landscapes.

V 4. SOIL DEVELOPMENT

V 4.1

Behaviour of Soil Phosphorus

The present author does not intend to discuss the phosphorus fractionation scheme used in this work, nor the ignition procedure for determination of P_o . Williams (1965) extensively reviewed the relevant literature and fully examined the scheme he adapted from earlier procedures, and some aspects of these were later discussed by Williams et al. (1967). Likewise, Syers (1966) and Williams and Walker (1967) have discussed the determination of organic P. This section will attempt to examine phosphorus in the pedogenesis of the Franz Josef Chronosequence.

There is ample evidence in Figs. 21 and 23-26 that large amounts of P may be lost from soils during pedogenesis. This corroborates work by Wild (1961) and contradicts Beadle (1962). Few of the arguments advanced by Beadle to refute Wild's work are valid with respect to the present work. The PM of the Franz Josef soils is not very low in P, nor has erosion removed surface horizons enriched in P. P may still be lost from soils or horizons of impeded drainage. Admittedly, P "lost" to the above-ground biomass has not been measured, but it was mentioned that the period from LW to Ok represents a phase of steady P loss (at about $0.03 \text{ g/m}^2/\text{annum}$) in a sequence of ecosystems probably having constant biomass. In other words, a relatively constant amount of P could be held sub-aerially while leaching of soil P continues unabated. P is held in "fixed" or occluded forms within the soil, but absolute amounts of these are not high and

the nett change over 22,000 years is small. The loss of very large amounts of P can be attributed to loss of acid-extractable Ca-P, either directly or as loss of forms into which the primary P is first converted. It may be calculated that if the water available for leaching of these soils is 100"/annum, and if the leachate contains only 0.1 p.p.m. of P, then the loss of P could amount to $0.25 \text{ g/m}^2/\text{annum}$. The measured rate is about a tenth of this, because P is retained against leaching in unweathered Composite samples, organic P, and the non-occluded and occluded forms of inorganic P.

Some data on inorganic phosphorus fractions in Stages I-VI were reported by Walker (1965, Table 3) and Williams (1965). In view of the ability of NH_4Cl to remove large amounts of P from highly-organic FH horizons (Williams et al., 1967) some analyses in Walker's Table 3 must be accepted with caution. However, it is evident from this Table that a considerable decline in acid-extractable Ca-P can occur in surface mineral horizons of even very youthful soils. Table 22A in the present thesis confirms this. Fig. 25 shows that the hypothesis of Chang and Jackson (1957) is in general valid for these soils. Chang and Jackson suggested that "Ca-P" is initially transformed into "Al-P", which then reverts to "Fe-P". Table 22A does not provide much evidence that $\text{NH}_4\text{F-P}$ is formed preferentially before 1st NaOH-P, except perhaps in LW 1.1. They then suggested that development of concretions and iron coatings during soil formation may later convert non-occluded forms into occluded forms of inorganic P. Fig. 25 shows a rapid initial loss of acid-extractable Ca-P and almost concurrent linear increase of non-occluded inorganic P. During the first millenium much

P in Composite samples is lost (see Nett Change Table in IV 5.) and converted to acid-extractable Ca-P (absolute amounts of which do not change), and thence to organic P (+ 51 g/m²) and non-occluded inorganic P (+ 19 g/m²), but occluded forms of inorganic P do not change greatly. The rate of dissolution of primary forms of P exceeds the rate of incorporation into non-occluded inorganic, and organic, P; and P may thus be lost from the profile. Moreover, the rate of formation of non-occluded inorganic P exceeds the rate of conversion to occluded forms, so the former accumulates for a considerable period of time. Fig. 24 shows an apparent steady-state of weights of non-occluded forms for 7000 years between UW and M, while occluded forms decrease, organic P does not change (Fig. 21) and residual inorganic P increases minimally. In this period the loss of acid-extractable Ca-P parallels the loss of ΣP_i . Lower amounts (and lower proportions) of occluded inorganic P in M with respect to UW may be a result of the highly gleyed nature of the older profile. Hsu and Jackson (1960) suggested that gleying may facilitate the formation of "Al-P" (NH₄F-P) rather than "Fe-P" (1st NaOH-P). Fig. 20 shows a considerable accumulation of "active" Al in this profile, and amounts of NH₄F-P were correlated, with highly significant coefficients, with weights of "active" Al.

Only a few studies have correlated soil P_o contents with other soil parameters, and the evidence is often inadequate, conflicting and non-comparable (Barrow, 1961). One investigation (John et al., 1964) on soils of British Columbia found the P_o content to be primarily dependent upon N and pH. Even fewer studies have considered P_o in relation to environmental conditions. Walker and Adams

(1959) derived an hypothesis relating changes in total and organic P to weathering and leaching regimes. This hypothesis was restated by Walker (1965). The present author's findings (Fig. 21) largely support the hypothesis. Soon after the initiation of soil formation the amount of P_o increases rapidly and after 1000 years attains an apparent steady-state, which is maintained for another 11,000 years. During this period weights of P_o in lower horizons do not increase greatly, but % P_o (of P_t) changes (Fig. 22). In the oldest soil a very high and uniform proportion of the P in all horizons is held in the organic form. The amounts of P_o formed during this sequence are not as large as in a Chronosequence on sands (Syers, 1966), probably because the native vegetation has slow growth-rates and low requirements for P. The coarse texture of the PM at Franz Josef may limit growth-rates and thus P_o accumulation. The apparent steady-state of weights of P_o from LW to M may be evidence for a constant biomass on soils formed from 1000 to 12,000 years ago. The decline in absolute amounts of P_o from M to Ok is probably due to the near-completion of weathering of coarse fractions by 12,000 years in the Mapourika soil, at which point little fresh primary P from stones or gravels may enter the ecosystem. It is suggested that the rapid decline of non-occluded inorganic P (Figs. 24, 25) from M to Ok is also due to this factor. The vegetation is forced to rely for its P upon P mineralised from P_o , and upon the declining non-occluded inorganic P. The previous balance of formation and mineralisation of P_o is shifted toward loss of P_o , because (i) less non-occluded inorganic P is available for plants; (ii) less plant tissue is formed, and so less P_o is formed; (iii) lower growth rates and absolute amounts of plant tissue require less P. Mineralised P in

excess of plant requirements is thus leached or is converted to occluded forms. In addition, absolute loss of P_o by leaching (perhaps within colloidal OM) must be an important pathway for loss of P_o . There is no way of resolving the relative importance of (i) direct leaching; (ii) mineralisation and conversion to decreasing amounts of plant tissue; and (iii) conversion to other inorganic forms, subsequently leached; in the loss of P_o . Nevertheless, a lengthy period of apparent steady-state is ultimately broken at a time when amounts of many other soil constituents are also declining.

There is little evidence in this Chronosequence study to support one part of Walker's hypothesis: that N-fixing plants are eliminated from the plant succession when all the acid-extractable Ca-P and plant-available forms of non-occluded inorganic P within root range have been converted to organic P or occluded forms of inorganic P. Admittedly, this situation may obtain in the surface horizons (wherein most roots are found) of quite youthful soils (LW, perhaps), but Carmichaelia grandiflora is moribund as early as Stage VII, and disappears from the succession before Stage IX. It may be true to say that any seedling Carmichaelia would have to establish in the FH layer above the mineral soil, and this material contains as much as 60% of its P in the organic form in Stage VI (Stevens, 1963). It has been shown (Fig. 14) that N continues to accumulate in the soil tessera long after the elimination of Carmichaelia grandiflora in Stage VII. This matter will be mentioned again later in this Discussion.

Retention of P in the Franz Josef soils against the severe leaching-potential is accomplished, obviously

rather inefficiently, by incorporation into plant tissue and subsequent accumulation of P_o , and by the development of occluded forms of inorganic P. It seems agreed (many papers, some reviewed by C.H. Williams, 1966) that although the capacity of soils to retain phosphate varies widely and may be influenced by many factors, such as pH, $CaCO_3$, clay mineral type and OM, the amount and nature of the free (or "active") oxides of Fe and Al are most important. Opinion now seems to be in favour of exchange-adsorption rather than the precipitation of discrete compounds such as strengite and variscite, or vivianite in gleyed soils. Calcium carbonate may sorb P in alkaline soils (Cole et al., 1953; Williams, 1965), but this was seen only in Stage I of the present Chronosequence and is clearly of no importance in all the older soils. Smith (1965) reviewed P sorption by Fe and Al oxides and stressed the conflicting nature of the literature on the topic. Saunders (1959) and Bromfield (1965) attributed P sorption very largely to "active" Al. Mention has been made (IV 5.) of the non-comparability of data on P sorption in this thesis with other published results. Consequently, it is not possible to determine which of the "active" elements is responsible for most of the P sorption measured under the specialised conditions of the inorganic P fractionation scheme. Nor is it possible to make any definitive statements about the severity of P sorption, or fixation, in the soils of the Franz Josef Chronosequence.

V 4.2

Podzolisation and Gleying

Any discussion of podzolisation and gleying as exemplified in the Franz Josef soils must consider the extent to which this Chronosequence demonstrates certain features characteristic of these soil forming processes. From the text (II 3.), Table 4 and Fig. 1, it would seem that profile morphology and site parameters, lessivage, exchangeable cations and disposition of "active" Fe and Al are suitable features upon which to base this examination.

There seems to be considerable confusion among pedologists (B.L. Elphick, pers. comm.) whether gleying includes the whole chain of processes initiated by reduction - reduction, mobilisation, translocation, re-oxidation and precipitation - or merely the first two or three steps. To include all five steps would give the term "gleying" a wider meaning than usually intended, for gleyed soils would then embrace all soils in which mottling is visible. In this thesis the terms "gleying" or "gleyed" refer to any soil or horizon in which "greying by reduction" is visible, while the term "gley soil" must be restricted to Intrazonal soils defined by E.J.B. Cutler (pers. comm.) as "soils of the hydromorphic end of a catena". None of the soils in this Chronosequence fall into this category, although peaty gleys similar to the soil at Point 1 in Fig. 1 are found at the foot of the slope below the Okarito profiles. On the other hand, "greying by reduction" is visible in many gleyed horizons of the soils in this sequence. A further complication, to which Franklin (1962) has drawn attention, is the seeming paradox of "gley podzols". The processes of podzolisation

require free drainage for their full expression, while gleying demands the reverse water regime. Creation during soil formation of horizons of low permeability within a podzol, and/or development of a thick greasy mor litter layer, may induce the secondary process of gleying. This will be discussed below with reference to this Chronosequence.

The profile descriptions (Appendix I) and Plates illustrate morphological changes throughout the Chronosequence. As early as 250 years after the start of soil formation, IX 1.3 is showing faint reddish colorations, which are even more evident in LW 1.3 and 1.4. LW 1.2 has some small indistinct areas containing bleached sand grains, which could be construed as a juvenile podzol A_2 , but equally could be gleying under a thin FH layer. The first strongly differentiated profile in the sequence is UW 1., which is a peaty gley podzol with a prominent iron pan (UW 1.3) which undoubtedly impedes drainage and promotes gleying in UW 1.2 above. UW 2.3 is not an impermeable pan, but UW 2.2 above is still gleyed, no doubt because of the overlying highly-humic .1 and FH layers. UW 2. is a peaty podzolised gley since it has no obvious iron pan. Both soils are Surface-Water Gleys. On the other hand, M 1. is a Ground-Water Gley and might almost be regarded as a gley soil, except that it is not at the hydromorphic end of a catena. In this soil the presence of a very deep FH layer and 10cm of highly-humic peaty loam and silty clay loam has not promoted gleying in the same manner as in UW. The variegated colours in M 1.3 and 1.4 are due to the active matrix gleying between highly-weathered and strongly-weathering stones and gravels. M 2. is more typical of a

peaty podzolised gley, as in UW 2.; but some matrix gleying due to ground-water is evident in M 2.4. The highly gleyed nature of Ok 1.3 is undoubtedly due to its massive structure and low porosity. After rain, water frequently flowed into the pit over the top of this horizon, which is much less developed in Ok 2. Thus, the younger soils demonstrate some degree of iron eluviation-illuviation prior to gleying in surface horizons after the development of poorly-permeable horizons such as iron-pans, or after the formation of water-logged highly-humic FH and .1 horizons. The exceptions to this trend are X 1. and 2., which are ground-water gleyed because of a high local water-table and compact subsoils of fine texture.

In the relevant section of the Review of Literature (II 3.2) some opposing views about lessivage and podzolisation were presented. Depth functions of %clay (Fig. 12) do not confirm assertions that lessivage is a necessary precursor to podzolisation in this Chronosequence. It is not until M 1. that the percentage of clay in the lower horizons resembles that in topsoils, and soils are well podzolised long before this point in the sequence. Little evidence can be advanced to differentiate between illuviated clay and clay formed in situ in lower horizons. The low %clay in Ok 2.1 and 2.2 is a real effect, since %clay is reported on an OM-free basis, but "puffing-up" of the topsoil by OM has reduced the weight/cm²/cm depth of mineral matter, and this horizon is now deeper than the equivalent depth of the same weight of mineral matter in youthful soils.

Many authors (see II 3.2) have agreed that a "conditioning" process of basic cation removal is necessary before podzolisation may be initiated. Franzmeier et al.

(1963) found that leaching of carbonates, basic cation removal, establishment of a pH gradient, phosphate mobilisation in the A horizon, and segregation of extractable Fe and Al all occurred concomitantly early in soil formation. Results reported in this thesis tend to confirm these statements. Carbonates are lost within a decade (Table 14A) and a pH gradient established (Table 10A). Rapid decrease of T.E.B. occurs within 250 years (Fig. 17) and loss of exchangeable cations, especially Ca^{++} , is also extremely rapid (Fig. 18). The onset of gleying in UW 1.2 and 2.2 does not appear to affect C.E.C., T.E.B. and %BS unduly. Deep and heavy FH layers on M soils have high C.E.C. values (m.eq.%), and this is also reflected in the eq./m^2 figures graphed in Fig. 17. T.E.B. has not been much affected by accretion of OM in M soils, but weights of exchangeable cations (Fig. 18) increase considerably. This is probably due to the final release of elements from decomposed rocks in these well-weathered soils. There is no evidence that exchangeable Mg^{++} forms a very high proportion of the exchange complex in gleyed horizons of this Chronosequence.

McKeague and Day (1966) extracted many different classes of soils with oxalate and dithionite solutions and reported (i) oxalate dissolves much Fe and Al from amorphous materials but little from crystalline oxides of these elements; (ii) oxalate-extractable Fe and Al gave a useful indication of B_f horizon development in many soils; and (iii) B_{fg} horizons in Gleysolic soils (Canadian nomenclature) often gave low oxalate-extractable iron due to accumulation of crystalline goethite. In the light of these observations conclusions drawn from Table 19A and Fig. 20 may be summarised below.

1. "Active" Fe, but not "active" Al, accumulates rapidly in young soils.

2. The accumulation of "active" Fe is depressed in all gleyed horizons, including lower horizons of X, except in M 1.4. This depression may be due to a mechanism similar to that outlined in (iii) above.

3. The formation of "active" Fe from rapidly weathering biotite and other ferromagnesian minerals must balance loss by leaching or conversion to inactive forms during the apparent steady-state from 5000 to 22,000 years. Weathering of feldspathic minerals may be slower, and hence less "active" Al is formed initially.

4. Depth functions clearly demonstrate an initial surface enrichment of "active" Fe, which subsequently moves steadily downward in the profile throughout the sequence VII - IX - LW - UW - M - Ok. This confirms the findings of Burges and Drover (1953) and contradicts Tamm, Aaltonen, and Mattson and Lönnemark (in Jenny, 1941).

5. "Active" Al does not exhibit any prominent depth gradients in soils younger than UW, and does not seem to have suffered eluviation-illuviation in company with "active" Fe. Gleyed horizons of M and Ok have large concentrations of "active" Al.

It seems to the present author that these points further confirm initial podzolisation, followed many years later by gleying of certain horizons. "Active" Al is not eluviated with "active" Fe during podzolisation of young soils because there is little of it available; and "active" Fe may not be detected in gleyed horizons by oxalate extraction.

V 4.3 Further Aspects of Soil Development, and Comparison with other Chronosequences

In its widest context, this study has attempted to investigate gains, losses, transformations and redistributions of elements within and between soils of a weathering and leaching continuum. Some of these changes have been discussed above; further aspects must now be briefly mentioned, before assessing the Franz Josef Chronosequence in the light of some similar sequences.

Changes with Time in the weights and proportions of gross soil separates and finer fractions of mineral matter have been illustrated in Figs. 9-12. These demonstrate the action of weathering in reducing particle-size and releasing mineral nutrients to the ecosystem. It is apparent that schists are rapidly weathered under a superhumid-microthermal climate. The first stage of weathering - physical disruption - may be visible in the field in LW, and is substantially completed after 12,000 years of soil formation. The continuous processes of chemical weathering find difficulty in supplying sufficient of some nutrients, such as P, after the store of elements within previously-intact stones is exhausted; hence the inevitable decline in soil fertility after Mapourika. This is demonstrated by graphs of C.E.C., oxid.C and N, exchangeable cations, and P_T , P_O and non-occluded inorganic P. At least four indices of weathering may be employed in soil sequence studies: index mineral determinations, optical and clay mineralogy, extraction of free iron and estimation of the ratio of extractable Fe to total Fe (Claridge, 1962), and changes in the forms of inorganic P (Chang and Jackson, 1957). In the present work only a little mineralogy has been done, and

there were indications of considerable weathering and rates of change in minerals. Barshad (1964) stated that even under intense weathering conditions the annual rate of clay formation might range from 0.0001 to only 0.002 g/100g PM. In the Franz Josef Chronosequence, this rate is 0.00018 g/100g PM. Some of this clay had expanded to 14Å lattice spacing. Weathering promoted accumulation of extractable Fe (Fig. 20) but the extractable/total ratio cannot be assessed. The decline of acid-extractable Ca-P is an excellent index of weathering because this form of inorganic P cannot increase in acid soils but must decline at a rate proportional to weathering intensity. The loss of acid-extractable Ca-P in this sequence is remarkably consistent, especially when expressed as a proportion of the sum of inorganic P fractions. The present author suggests that this soil parameter might even find use as a geochronological tool in certain circumstances.

Crompton (1960) coined the term "richness of weathering" to describe the rate at which the soil solution may be enriched by weathering minerals. This enrichment will be countered by the "intensity of leaching", itself a factor of climate, topography and profile permeability. The effects of leaching will also be balanced by the organic cycle. The soils of the Franz Josef region are undoubtedly subjected to extremely intense leaching, which is partly offset by weathering and the organic cycle only until few fresh minerals are available after some 12,000 years of soil development. B.B. Polynov (in Crompton, 1960) suggested that Ca^{++} , Mg^{++} and K^{+} had relative rates of mobility (expressed against Cl^{-} as 100) of 3.00, 1.30 and 1.25 respectively. Loss-rates of total Mg and K derived from regressions do

not confirm these mobility-rates: K is lost at $0.9 \text{ g/m}^2/\text{annum}$, which is 4.5 times faster than Mg. This may be due to the prevalence of K-containing minerals in these soils and rapid physical comminution of mica schists.

Walker and Adams (1959) and Walker (1965) have propounded an hypothesis relating total and organic P to amount of weathering and leaching, or passage of Time. According to this hypothesis, the accumulation of N in an ecosystem must cease when all plant-available forms of P reach a minimum through conversion to organic P or occluded inorganic P, loss by leaching, or inadequate rates of mineralisation from organic P. While it was shown above (V 4.1) that the elimination of Carmichaelia grandiflora from the succession occurs long before plant-available forms of P are at a minimum, it is significant that amounts of oxid.C and N decline (Fig. 14) in company with non-occluded inorganic P and organic P, after most of the acid-extractable Ca-P has also been lost (Figs. 24 and 25). The data in this thesis therefore directly support the hypothesis, originally derived from grassland soils of indeterminate age.

Accumulation of N at a rate of about $0.044 \text{ g/m}^2/\text{annum}$ between VII and M, in the complete absence of Carmichaelia grandiflora or other known macro-N-fixer, is interesting. The identification of the source of this N must await careful microbiological and radioisotope studies, but such a small annual increment of N could easily be supplied by utilization of N in rainwater containing about 0.5 kg/ha/annum of N. The abundant West Coast rain, falling so near the sea, could undoubtedly supply this small amount of N, even in the complete absence of free-living N-fixing micro-organisms. The N will continue to be incorporated

within the vegetation just so long as plant-available P is present. C/N ratios rise considerably during the period of low N supply after the elimination of the macro-N-fixing species, as Walker postulated. In addition, C/P_o ratios (mean of two pits, mineral soil + FH) rise from 154 in VII to 296 and 350 in M and Ok respectively, as predicted by Walker.

It is evident from Jenny's writings on Soil Forming Factors that he entertained hopes of building a system of truly quantitative pedology, based on data from many and varied sequences. The cynical soil scientist would assert that such hopes will never be realised: monosequences are so rare and study of them so difficult. The limited number of reliable Chronosequences so far reported confirm this observation. Moreover, it is very hard to compare and contrast the conclusions made from them. Firstly, all sequences have failed in one way or another to exercise due and proper control over the Soil Forming Factors other than Time. Secondly, all are in quite different regions with features peculiar solely to each individual sequence. For example, in the present Chronosequence, stones and gravels play no pedogenetic role in youthful soils, but are incorporated into the pedogenetic process in older soils. Thirdly, each study reports differing soil parameters, often determined by varying analytical methods. Perhaps the ambitious earthworks prepared by Proudfoot (1965) represent the first proper Chronosequence study, provided interest and uniformity of investigation can be maintained for 128 years!

Nevertheless, the picture is not entirely dismal, for many sequences can be compared at least qualitatively. The most striking point is that the similarities between

several Chronosequences are more numerous than the differences. All studies report an initial decline in topsoil pH and content of carbonates and basic cations, leading to the establishment of depth gradients. Likewise, all studies show that OM, with associated C and N, accumulates first on and in the surface of the mineral soil. In some sequences this represents the only visible horizon differentiation. Lastly, many sequences have a vegetation succession with N-fixing plants in the youthful communities, and there is usually a "transition" period during which the N-fixers are eliminated, leaving other plants to utilise the accumulated N.

Data in the present thesis confirm some of the observations of Dickson and Crocker (1953/54), Crocker and Major (1955), and Crocker and Dickson (1957). The 1955 and 1957 studies in Glacier Bay and near the Herbert and Mendenhall Glaciers in Alaska are most comparable with the present work. During the first half-century of soil formation, OM, C and N did not accumulate as fast as Franz Josef as in Alaska, probably because the coarse substrate restricted plant growth. Alder is a more efficient N-fixer than Carmichaelia grandiflora, and its litter return much greater. Both in Alaska and New Zealand an absolute decline in weight of N (Fig. 16 in this thesis) was observed soon after the "transition" to associations lacking N-fixing plants. In all sequences the rate of accumulation of N markedly decreased at this time, and C/N ratios increased. At Franz Josef and Herbert/Mendenhall the weight of N in the mineral soil increased at a very low rate after the "transition", despite translocation to vegetation from the "forest floor". In both Alaskan studies this effect was considered real, and

ascribed to the utilization of N by rapidly-growing spruce. Data in the present study also confirm in a qualitative fashion data reported by Goldthwait et al. (1966). They found 16.6 m/eq.% C.E.C. in an organic-rich mineral horizon of their oldest (250 years) soil, which is identical to the C.E.C. of IX 2.1.

Finally, a point made above concerning non-comparability of studies is particularly apposite with reference to the excellent work of Franzmeier et al. (1963). It is frustrating to find that the Michigan and New Zealand studies have only a few points of contact, most of which have been mentioned at various times earlier in this Discussion.

V 4.4

Conclusions

Some morphological and chemical changes throughout the sequence are depicted in a qualitative fashion in Fig. 27, patterned after similar diagrams in Arnold (1965). While this is in no way comprehensive, it may serve to illustrate changes in FH, gleyed, iron-enriched and weathering horizons. Simultaneous gleying and iron enrichment in M is shown by dispersed symbols for the latter. The loss-gain arrows below the Time-profile are merely attempts to indicate relative magnitudes of various chemical parameters, and cannot be scaled against regressed figures presented earlier. Nevertheless, the present author believes such a presentation is worthwhile in this context, although Arnold originally used models like these for a different purpose.

Rode (1961), in addition to categorising the present and all other Chronosequence studies as "comparative geography", stated that the well-known irreversible processes of pedogenesis may be divided into two phases. The first, during which soil changes occur rapidly, is followed by a period of indeterminate length in which apparent steady-states, or dynamic equilibria, of many soil parameters may be observed. Dickson and Crocker (1953/54) likewise divided soil development into two phases: (i) the germination and survival of the effective disseminules, giving profiles with upper layers dominated by OM and lower layers carrying the impress of the inorganic PM; and (ii) the later evolution of the profile due to weathering and eluviation-illuviation processes. Many previous studies, reviewed earlier (II 1.3), did not extend over long enough periods of time to observe apparent

steady-states in soil characteristics. The present study is probably the first in which a "moderately-controlled" Chronosequence has not only covered periods of dynamic equilibrium, but has also demonstrated soil degradation after equilibrium. Accordingly, Rode's hypothesis may be strongly supported, but with the reservation that only a few soil parameters demonstrate apparent steady-states, often transiently. The data in this thesis have shown that very low rates of change over varying periods of time are achieved in pH, total soil N (250-500, 1000-5000 years), total soil oxid.C (500-1000 years), T.E.B. (essentially 250-22,000 years), total tessera Mg and Ca (250-22,000 years) and K (12,000-22,000 years), "active" Fe (5000-22,000 years), P_o (1000-12,000 years) and non-occluded inorganic P (5000-12,000 years). Several of these parameters, chiefly those closely associated with OM, have very rapid rates of change during the first millenium of soil development. A period of ultimate soil degradation after 12,000 years is illustrated by loss of N and oxid.C, C.E.C., exchangeable Ca^{++} and Mg^{++} , P_o , and non-occluded inorganic P. Total P and acid-extractable Ca-P decline throughout the whole sequence. Lastly, soil characters associated with weathering, such as amounts of stones, gravels, sands, silt and clay, do not demonstrate any appreciable periods of apparent steady-state, but change continuously though often imperceptibly.

If I may be permitted to use the personal pronoun, I believe strongly that Science, and especially Soil Science, must be the handmaiden of utilization. A study of this kind would remain an academic exercise without some attempt to place it in the context of land-use in Westland. Accordingly, a few random thoughts may be

relevant. This investigation, although incomplete and flawed, may have thrown some light on problems of land-use associated with soils. After trial and much error agriculture is now mainly restricted to youthful soils on low terraces near the major Westland rivers, but even these present problems to the farmer. Puddling by stock, despite stoniness of soils, may be attributed to weakly developed fine crumb structures in topsoils formed under forest vegetation. Even though often rejuvenated by floods, many of these youthful soils are becoming deficient in P and K. Some data in this thesis have shown how rapidly these nutrients may be lost from Westland soils. Amounts of N in agricultural soils are often very low, no doubt because N fixed by legumes or non-leguminous N-fixers following deglaciation was not retained within the ecosystem when forests were cleared for agriculture. Soils in this Chronosequence rapidly developed features which ensured their intractability for agriculture: compact B horizons; deep, greasy, highly-humic litter layers and topsoils; gleyed poorly-permeable horizons; and, especially, iron pans of varying thickness. The latter have been particularly troublesome in land development; deep rippers and even explosives have been used to shatter the pans and facilitate drainage. Such violent methods are often to no avail, since lateral drainage through compact cemented horizons is negligible. However, some success is now being achieved by surface drainage, and subsequent establishment of a compact sole of grasses and clovers. Attempts to use Okarito soils near Hari Hari and Mahinapua for exotic forests have in the main been silviculturally disastrous. I would like to feel that this study might help to

elucidate ways of achieving rational and successful land-use in Westland, especially if this devolves upon the aesthetically pleasing alternative of leaving the land to the rimu and the rata, the raging river and the creeping glacier!

VI

SUMMARY

1. A Chronosequence of soils from zero to 22,000 years of age on stony alluvial and outwash terraces and moraines near the retreating Franz Josef Glacier was recognised, described and investigated.
2. An extensive review of literature pertaining to Chronosequences, geochronology, podzolisation and gleying, podocarp successions in New Zealand, and an earlier study of a Chronosequence of youthful soils at Franz Josef indicated relevant aspects of topics related to the present investigation.
3. The field and laboratory activities were described.
4. The vegetation succession, shown in site descriptions, passed from associations containing Carmichaelia grandiflora (a native legume) on youthful soils, to slightly podzolised soils under rata, kamahi and young podocarps, to mature podocarp-hardwood forests on well developed gley podzols. Silver pine was a prominent member of the association on the oldest soil.
5. Initial soil changes were correlated with rapid accumulation of organic matter on and in the surface mineral soil. These included rapid decrease in pH, accumulation of oxidisable carbon and nitrogen over 55 years at 30.8 and 2.23 g/m²/annum in mineral soil + FH, complete loss of carbonates within a decade, and establishment of depth gradients within the soil profile. Acid-extractable calcium-bound phosphorus was leached, or changed to organic and/or forms of inorganic phosphorus early in soil formation.
6. Soil morphogenesis was illustrated by detailed profile descriptions and colour photographs. A well-differentiated gley podzol formed from virgin parent

material within 5000 years after the initiation of soil formation.

7. Organic matter accumulated in and on the soil at a mean rate of approximately $4 \text{ g/m}^2/\text{annum}$ over the first 12,000 years of pedogenesis. The rate of accumulation was considerably greater than this in very young soils.

8. The total weight of soil in a tessera declined with age. Stones, and coarse and fine gravels, weathered to form fine material smaller than 2mm.

9. Not only did the weight of fines increase with age (from 9% to 86% of tessera weight), but these fines themselves were weathered to reduce the proportions of coarse sand from about 85% to 15%, with concomitant large increases in fine sand and silt, and small increases in clay at the rate of $0.00018 \text{ g/100g parent material/annum}$. Less than half the gain in fine sand from coarse sand was converted to silt.

10. Oxidisable carbon and nitrogen increased to 21.71 and $0.814 \text{ kg/m}^2/75\text{cm profile}$ (mean of two pits) respectively in 12,000 years, at overall approximate rates of 1.5 and $0.044 \text{ g/m}^2/\text{annum}$. Carbon/nitrogen ratios generally widened with age to values as large as 77.4 in litter and 45.9 in FH layers. Amounts of oxidisable carbon and nitrogen held in litter and FH layers increased greatly until 12,000 years passed, but the proportions held there with respect to the underlying mineral soil generally decreased with age.

11. Cation exchange capacity increased rapidly for 12,000 years and then declined, whereas total exchangeable bases maintained approximately the same level throughout the sequence. Most upper horizons had a base saturation

of 15-20%, and lower horizons had almost negligible percent base saturation.

12. Multiple regressions of cation exchange capacity, percent oxidisable carbon and percent clay for 69 mineral soil horizons, arranged in various groups of young and old soils, and upper and lower horizons, invariably confirmed that oxidisable carbon was the overwhelmingly important factor in determining cation exchange capacity in these soils.

13. Total potassium was lost from the soil tessera at $0.9 \text{ g/m}^2/\text{annum}$; 4.5 times faster than loss of total magnesium.

14. Large amounts of total sulphur in the parent materials were rapidly oxidised to give low concentrations in lower horizons with concomitant accumulations in upper horizons, presumably organic-bound. Gleyed horizons had high levels of total sulphur, probably much of it as sulphide.

15. Accumulation of "active" (oxalate-extractable) iron was depressed in gleyed horizons, in which accumulation of "active" aluminium was enhanced. The zone of maximum accumulation of "active" iron moved downward in the profile throughout the sequence.

16. Over 90% of the phosphorus in the soil tessera was lost at $0.0487 \text{ g/m}^2/\text{annum}$ over the whole sequence, or at $0.0298 \text{ g/m}^2/\text{annum}$ during the period from 1000 to 22,000 years after the start of pedogenesis.

17. Amounts of organic phosphorus increased rapidly during the first 1000 years of pedogenesis, maintained an apparent steady-state for 11,000 years, and then declined slightly during the following 10,000 years. The proportion

of total phosphorus held in the organic form reached 70% in upper horizons of young soils, and over 80% of total phosphorus in all horizons of the oldest soil was organic-bound. Carbon/organic phosphorus ratios increased from 154 in the century-old soil to 296 and 350 in soils 12,000 and 22,000 years of age respectively.

18. Many complex changes in forms of inorganic phosphorus may be summarised as follows: against the background of declining total phosphorus, acid-extractable calcium-bound phosphorus was first converted to non-occluded and then occluded inorganic phosphorus. Some primary phosphorus became organically-bound; and phosphorus in primary, organic and non-occluded forms was lost from the soil by leaching. Virtually all the phosphorus in the parent material was in the primary form, but the oldest soil contained no primary phosphorus. About 80% of the total phosphorus in the oldest soil was organically-bound; and the remnant 20% of inorganic phosphorus comprised about 20%, 50% and 30% of non-occluded, occluded and residual inorganic phosphorus respectively.

19. X-Ray Diffraction studies of sands, silts and clays in a few selected soils traced the appearance of clay-size quartz in the older soils, loss of plagioclase, chlorite and mica with age, and increase of hydrous mica.

20. The operation of the organic cycle in concentrating many elements in upper horizons was clearly demonstrated.

21. A lengthy discussion first commented upon the extent to which the four Soil Forming Factors other than Time had been held "constant or ineffectively varying".

The experimental methods used in the study were criticised, and suggestions made for further research.

22. The latter part of the discussion centred around soil formation under the headings of behaviour of phosphorus, podzolisation and gleying, comparison with other Chronosequences, and conclusions. Important points included:

(i) An hypothesis proposed by Walker, which linked changes in amounts and forms of phosphorus with declining ecosystem nitrogen content, and with degree of soil development, was substantially confirmed.

(ii) Soils of the Franz Josef Chronosequence were first podzolised, and later gleyed in certain horizons.

(iii) Very low rates of change for varying periods of time (apparent steady-states) were achieved in pH, and total soil nitrogen, oxidisable carbon, magnesium, calcium, potassium, "active" iron, organic phosphorus, and non-occluded inorganic phosphorus. Total phosphorus and acid-extractable calcium-bound phosphorus decreased throughout the sequence. A period of ultimate soil degradation after 12,000 years of pedogenesis was illustrated by loss of oxidisable carbon, nitrogen, cation exchange capacity, exchangeable calcium and magnesium, organic phosphorus and non-occluded inorganic phosphorus. It was suggested that this degradation was consequent upon the completion of physical comminution of stones and gravels after 12,000 years of soil formation, whereupon no further minerals from freshly-weathered rock could enter the pedogenetic process.

(iv) The relevance of the present study to some aspects of land utilization in Westland was discussed briefly.

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